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Mining Research Laboratories

Laboratoires de recherche minière

Canada

AIRBORNE DUST IN MINES
PUBLISHED REPORTS 1960-1987

G. Knight

Volume 2 MRL 88–115 (R)

Energy, Mines and Resources Canada
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AIRBORNE DUST IN MINES — PUBLISHED REPORTS: 1960-1987 CANMET/MINING RESEARCH LABORATORIES

Volume 2—ASSESSMENT, IN-MINE STUDIES, ETC.

POUSSIÈRE AÉROPORTÉE DANS LES MINES— RAPPORTS PUBLIÉS: 1960-1987 CANMET/LABORATOIRES DE RECHERCHE MINIÈRE

ÉVALUATION, ÉTUDES DANS LES MINES, ETC.

G. Knight

Canadian Mine Technology Laboratory

Laboratoires canadiens de technologie Minière

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CANMET MINING RESEARCH LABORATORIES.
Divisional Report MRL 88-115 (R)

MICROMEDIA

FOREWORD

For many years an important aspect of the work of the Elliot Lake Laboratory has been studies of airborne dusts in underground mines. Several aspects have been addressed including: the development of instrumentation; in-situ studies; the characterization of airborne dusts; and, more recently, dust control and abatement.

Geoffrey Knight, one of the Division's senior scientists, has been associated with that work, often as project leader, for much of the period covered by this report. It was his initiative that resulted in the publications being brought together as a collection. It is our hope that this document will be useful both to the mining industry and to the universities in this important field.

John E. Udd
Director,
Mining Research Laboratories

AVANT-PROPOS

Depuis plusieurs années déjà, le Laboratoire d'Elliot Lake consacre une partie importante de ses activités à l'étude des poussières aéroportées dans les mines souterraines. À ce jour, les scientifiques se sont penchés sur plusieurs problèmes dont le développement de l'appareillage, les études in situ, la caractérisation des poussières aéroportées, et plus récemment, le contrôle et la réduction des concentrations de poussières.

Geoffrey Knight, un des scientifiques principaux de la Division, a participé aux recherches, maintes fois à titre de chef de projet, pendant la plus grande partie de la période couverte par ce rapport. Grâce à son esprit d'initiative, les publications ont pu être rassemblées en une collection. Nous espérons que le présent document constituera un outil précieux pour l'industrie minière et les universités qui s'intéressent à la recherche dans ce domaine.

John E. Udd
Directeur,
Laboratoires de recherche minière

Airborne Dust in mines — Published Reports: CANMET/Mining Research Laboratories, 1960-1987

by

G. Knight*

ABSTRACT

This publication reproduces the reports published in journals, etc. by the Elliot Lake Laboratory, Dust Section, and by cooperating organisations on dust topics. The published documents, 35 in total, are given verbatim. They are divided into six main sections: 1, Dust Sampling and Assessment; 2, Dust Assessment; 3, Mine Studies; 4, Dust Characterization; 5, Dust Standards and Assessment Principles; and 6, General.

The three appendices list: 1, A list of the about 200 internal reports on dust topics that have been prepared; 2, A list of the major reports on control of diesel engine exhaust particulates; 3, A list of the research contracts carried out on dust topics on behalf of CANMET.

There is considerable overlap between the first and second sections. The first includes all papers on dust sampling and joint papers on dust sampling and assessment, the second includes those papers restricted to assessment. The split was introduced to balance the two volumes.

Keywords: Respirable dust; Dust sampling; Dust control; Dust measurement; Quartz assessment

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Contrôle de la poussière aéroportée dans les mines
Rapports publiés : CANMET/Laboratoires de recherche minière
1960-1987

par

G. Knight*

RÉSUMÉ

La présente publication comprend les rapports publiés sous forme d'articles de journaux, etc. par le Laboratoire d'Elliot Lake, Section de recherche sur la poussière, et par divers organismes qui collaborent à la rédaction d'articles sur le sujet. La documentation comprend, au total, 35 articles qui sont publiés textuellement et classés dans six catégories principales ; 1, Echantillonnage et évaluation de la poussière; 2, Évaluation des taux de poussière; 3, Etudes des conditions environnementales dans les mines; 4, Caractérisation de la poussière; 5, Normes relatives aux taux de poussière acceptables et principes d'évaluation; et 6, Généralités.

Les trois annexes comprennent : 1, Une liste d'environ 200 rapports de divisions portant sur le contrôle de la poussière; 2, Une liste des rapports principaux sur le contrôle des particules des gaz d'échappement diesel; 3, Une liste des contrats de recherche qui ont été réalisés pour le compte de CANMET dans le domaine du contrôle de la poussière.

La première et la deuxième section sont étroitement liées. La première section comprend tous les documents relatifs à l'échantillonnage de la poussière ainsi que des articles sur l'échantillonnage de la poussière et l'évaluation des taux de poussière acceptables et la deuxième inclut tous les documents qui ne portent que sur l'évaluation des taux de poussière. Les documents sont présentés de cette façon afin que les deux volumes se complètent.

Mots-clé : Poussière inhalable; Échantillonnage de la poussière; Contrôle des taux de poussière; Mesure des taux de poussière; Evaluation du quartz.

*Chercheur scientifique, Laboratoire canadien de technologie minière, CANMET, Énergie, Mines et Ressources Canada, Ottawa (Ontario).
Anciennement au service du Laboratoire d'Elliot Lake

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INTRODUCTION

The underground-environment dust studies have, over the past 27 years, been directed at three main topics: dust measurement instrumentation; in mine studies and dust characterization. The studies carried out under dust measurement instrumentation have had four major objectives. First, the comparison of the types of dust sampling instruments in wide use throughout the world in pure mineral dust clouds prepared in the laboratory. These studies were mainly carried out in the period 1965 to 1970 and culminated in the CANMET report R250 (1971). Second, the development of dust sampling techniques for routine use in mines. The main emphasis has been on a combined size-selective sampling and quartz analysis technique culminating in the CANMET Report 78-7 (1978). This technique was intended for routine use in mines and has been adopted,with modifications, in many Canadian mines. Third, continuous monitoring could be a useful technique for improving mine environment and some studies have been carried out. Fourth, Asbestos fibre in asbestos mines and mills as well as other mines is a potential health hazard and a limited effort has been directed to it. The potential health effects have been a major limiting factor in commercial use of asbestos and thus in Canadian production and exports.

The in-mine studies have been directed to three major objectives: Measurement of dust levels using the newly developed technique, gravimetric with quartz assessment; identification and quantification of the major dust sources in mines; and dust control techniques.

Dust characterization has been regarded as having long term objectives after developing and applying dust sampling techniques capable of determining the first order exposures of miners to dust namely total respirable dust and respirable quartz dust. The studies carried out have essentially been spare time, combined with other studies or directed at special problems.

The published papers are given verbatim in chronological order in each of six categories as follows:

1. Dust Sampling and Assessment
2. Dust Assessment
3. In-Mine Studies
4. Dust Characterization– composition and size distribution
5. Dust Standards and Assessment Principles
6. General

Dust instrumentation was split into two categories to balance the two volumes. There is overlap between the two and the first section includes the papers on dust sampling and on both sampling and assessment; the second is those restricted to assessment. Because the papers are reproduced as published the page numbering is erratic and each paper is treated as a chapter in a section. The chapters in each section are numbered consecutively with both section and chapter numbers. Each chapter has a coloured title page, each section uses a different colour. This is followed by a listing of the many internal reports by both MRL and other cooperating CANMET laboratories on underground- environment dust topics. This listing is an expansion of that given by M.G. Grenier and K.C. Butler in 'Index of underground dust reports: CANMET/Mining Research Laboratories,1960-1985' CANMET Special Publication SP86-4 (1986).

This report does not include all the dust related research carried out by the Canadian Explosives Atmospheres Laboratory of MRL in their Diesel engine exhaust control program or the coal mine dust studies carried out by the CANMET Coal Research Laboratory. A list of the major papers on heavy-duty diesel emission control is given in appendix B.

Appendix C lists the studies carried out by other organisations under contract to CANMET relevant to the dust topics included.

ACKNOWLEDGEMENTS

The author wishes to acknowledge the assistance of many colleagues and cooperating organisations in carrying out many of the studies reported in these papers. In particular the following organisations have made major contributions: Mines Accident Prevention Association of Ontario; McIntyre Research Foundation; the Labrador Institute of Northern Affairs, Memorial University; and the Quebec Asbestos Mining Association. The contributions of the staff from many mines has been very helpful.

INTRODUCTION

Les recherches réalisées au cours des vingt-sept dernières années sur le contrôle de la poussière dans les mines souterraines portaient sur trois sujets principaux : le développement d'un appareillage pour mesurer les concentrations de contaminants, l'environnement minier, et la caractérisation de la poussière. Les études portant sur des instruments de mesure des concentrations de poussière visaient quatre objectifs. D'une part, on a cherché à établir une comparaison entre les instruments d'échantillonnage de la poussière utilisés à l'échelle mondiale au moyen de nuages de poussière minérale préparée en laboratoire. La plupart des études ont été menées dans la période de 1965 à 1970 et ont abouti à la publication par CANMET du Rapport R250 (1971). D'autre part on a tenté de développer des techniques d'échantillonnage de la poussière pouvant être utilisées régulièrement dans les mines. Les recherches ont porté principalement sur le développement d'une technique d'échantillonnage d'après la taille des grains des particules combinée à la technique d'analyse du quartz. Un compte rendu des travaux de recherche a été publié dans le rapport 78-7 (1978) de CANMET. Cette technique est destinée à être utilisée régulièrement dans les mines et a été sélectionnée, moyennant quelques modifications, pour utilisation dans plusieurs mines canadiennes. En troisième lieu, la surveillance en continu qui pourrait s'avérer une technique utile pour améliorer l'environnement minier, à fait l'objet de certaines études. Enfin, les particules de fibres d'amiante dans les mines d'amiante et dans les installations de broyage de même que certaines installations minières constituent des sources potentielles de danger et sont à l'étude. Les effets néfastes qu'elles pourraient avoir sur la santé des travailleurs ont été le facteur principal sur lequel on s'est fondé pour limiter la production commerciale de l'amiante au Canada de même que l'exportation du produit.

Les études qui ont été réalisées dans les mines visaient trois objectifs : la mesure des concentrations de poussière au moyen de la nouvelle technique, l'analyse gravimétrique y compris l'évaluation du quartz; l'identification et la quantification des sources principales de poussière dans les mines; et les techniques de contrôle des concentrations de poussière.

Les recherches portant sur la caractérisation de la poussière comportent des objectifs à long terme. Cependant, on doit, au préalable développer et appliquer des techniques d'échantillonnage capables de déterminer chez les mineurs les premiers signes d'exposition aux contaminants, y compris l'exposition à la poussière entièrement inhalable et à la poussière de quartz. Les études ont presque toutes été réalisées à temps perdu, dans le cadre de recherches sur d'autres sujets ou sur des problèmes particuliers.

Les documents sont présentés dans l'ordre chronologique et classés dans l'une des six catégories qui suivent :

1. Échantillonnage et évaluation des concentrations de poussière
2. Évaluation des concentrations de poussière
3. Évaluation des conditions environnementales dans les installations minières
4. Caractérisation de la poussière - composition et distribution granulométrique
5. Normes relatives au contrôle de la poussière et principes d'évaluation
6. Généralités

Les articles sur les instruments de mesure des concentrations de poussière sont répartis en deux catégories de façon à ce que les deux volumes se complètent. La première et la deuxième section sont étroitement reliées, la première section comprenant des articles sur l'échantillonnage de la poussière de même que sur l'échantillonnage et l'évaluation tandis que la deuxième section porte uniquement sur l'évaluation. Les documents étant réimprimés sous leur forme originale, le numérotage des pages n'est pas ordonné et chaque document constitue un chapitre. Dans chacune des sections, les numéros des chapitres se suivent. La page titre de chacun des chapitres apparaît en couleur, et une couleur particulière différencie chacune des sections. Une liste des nombreux rapports de divisions préparés par LRM ou d'autres laboratoires qui collaborent à la rédaction d'articles sur le contrôle de la poussière dans le milieu minier souterrain est ensuite présentée. La liste complète celle qui a été compilée par M.G. Grenier et K.C. Butler lors de la puiblication du "Répertoire des rapports sur le contrôle de la poussière : CANMET/Laboratoires de recherche minière, 1960-1985" Publication spéciale de CANMET-SP86-4 (1986).

Le présent rapport ne comprend pas tous les articles sur le contrôle des concentrations de poussière publiés par le Laboratoire canadien de recherche sur les atmosphères explosives de LRM dans le cadre du programme sur le contrôle des émissions diesels ou les rapports des études sur le contrôle de la poussière dans les mines réalisées par le Laboratoire de recherche sur le charbon de CANMET. Une liste des documents les plus importants qui ont été publiés sur le contrôle des émissions diesels est présentée à l'annexe B.

L'annexe C comprend le répertoire des études effectuées en sous-traitance pour le compte de CANMET par d'autres organismes et qui ont rapport aux sujets traités.

REMERCIEMENTS

L'auteur de ce rapport désire remercier ses collègues et les organismes qui ont participé aux recherches dont il est question dans ces documents. La collaboration des organismes suivants a été des plus précieuses : Mines Accident Prevention Association of Ontario; McIntyre Research Foundation; the Labrador Institute of Northern Affairs, Memorial University; et l'Association des mines d'amiante du Québec. La participation du personnel de plusieurs installations minières a également été très appréciée.

2. 11

Section 2—Chapter 11

The Electronic Scanner—An Instrument for the Rapid Counting of Konimeter Dust Spots

by

P. Chmara

The Canadian Mining and Metallurgical(CIM) Bulletin
62(691) pp1171-4 (1969)

ENVIRONNEMENTS DES MINES
LEUR CONSTITUTION ET LA FAÇON DE LES CONTRÔLER

LE DÉTECTEUR À BALAYAGE ÉLECTRONIQUE - UN INSTRUMENT DE COMPTAGE RAPIDE DES CONCENTRATIONS PONCTUELLES DE POUSSIÈRES DANS LE CONIMÈTRE

PETER CHMARA, Ingénieur en chef de la ventilation
Mines Accident Prevention Association of Ontario
North Bay, Ontario

RÉSUMÉ

Depuis 1926, on mesure les concentrations de poussières présentes dans les mines de l'Ontario par le procédé de conimétrie, en conformité avec l'expérience et les méthodes des Sud-Africains. L'introduction d'un programme volontaire de relevés semi-annuels des conditions atmosphériques dans toutes les installations de l'ensemble des mines de l'Ontario a rendu indispensable l'élaboration d'un instrument qui permettrait d'évaluer rapidement et précisément les concentrations ponctuelles de poussières dans le conimètre. On estime que la mise au point de l'appareil de balayage électronique répondra à ce besoin. On décrit dans cet article un programme au cours duquel les prélèvements ponctuels faits avec des conimètres dans des mines de l'Ontario, feront l'objet d'un dénombrement dans les bureaux régionaux de la Mines Accidents Provincial Association of Ontario à North Bay.

MINE ENVIRONMENTS –
THEIR MAKEUP AND CONTROL

The Electronic Scanner — An Instrument for the Rapid Counting of Konimeter Dust Spots

PETER CHMARA, Senior Ventilation Engineer,
Mines Accident Prevention Association of Ontario,
North Bay, Ont.

ABSTRACT

The measurement of dust concentration in Ontario mines since 1926 has been accomplished by konimetry, based on South African experience and methods. The introduction of a voluntary program of semi-annual surveys of air conditions at all operations throughout Ontario mines created a need for an instrument that would assess konimeter spots rapidly and accurately. The development of the Electronic Scanner, it is felt, answers this need. A program whereby all konimeter spot samples taken at Ontario mines will be counted at the MAPAO field offices in North Bay is described.

INTRODUCTION

VARIOUS UNSUCCESSFUL ATTEMPTS have been made in the past to reduce the time consumption and the eye-strain involved in the counting of dust particles on konimeter slides. The practice of konimetry for measuring dust concentration in the mining industry is well known and has been described by Norman[1] and Arnott *et al.*[2]. This paper reviews the development and describes the recent application of the Electronic Scanner for rapidly counting dust particles on slides.

PETER CHMARA was born in Oshawa, Ontario. He graduated from the University of Toronto in 1951, receiving a mining degree in Applied Science and Engineering.

He gained his experience in various Northern Ontario mines as a student miner, and on graduation spent several years as a safety and underground supervisor at Canadian Johns-Manville Company's Jeffrey Mine in Quebec. In 1958, he was instructor in the Mining Engineering Department of the University of Toronto for a year previous to joining the M.A.P.A.O. as ventilation engineer in mid-1959.

THE PAPER WAS PRESENTED: during a Coal Division session at the Annual General Meeting of the Institute, April 22, 1969.

KEYWORDS: Electronic Scanner, Mine environments, Dust sampling, Konimeters, M.A.P.A.O., Microscopy, Ventilation.

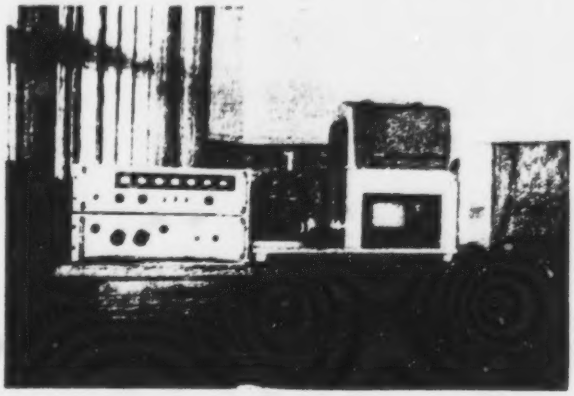

Figure 1.—The Electronic Scanner.

Konimeter slides, mailed from various mines in Ontario, are being processed at the field office of the Mines Accident Prevention Association of Ontario (MAPAO), North Bay, Ontario.

DEVELOPMENT

Through the joint sponsorship of MAPAO and the McIntyre Research Foundation, the Scanner was developed by T. R. Flint at the Federal Mines Branch under the guidance originally of Dr. G. G. Eichholz and, latterly, Dr. John Keys. Early test work and construction of the Scanner has been described by Flint[3].

DESCRIPTION OF EQUIPMENT

The Electronic Scanner comprises five major components (*Figure 1*): a konimeter microscope, a television camera, a monitor, a specially designed scaler control unit and a high-speed scaling unit.

The picture image on a television screen is composed of a sequence of horizontal lines, each picture containing 525 lines. These lines are traced on the screen at the rate of 15,750 lines per second, resulting in the reproduction of each picture at the rate of 30 times per second. At this rate of reproduction, a flickering image would result. To avoid this flicker, two sets of images composed of 262½ horizontal lines are scanned at the rate of 60 times per second. This rate of scan is well above the threshold of visual retention. The two sets of scans are interlaced so that the second set scanned falls precisely between the lines of the first set and vertical detail is retained.

An optical focused image, falling on the photosensitive target of the vidicon tube, produces areas of varying brightness. When a fine beam of electrons is swept across the tube, these areas produce variations of current in the beam which, when amplified, provide the picture signal. The electron beam is swept from left to right and top to bottom in a sequence of 525 interlaced lines, as outlined earlier. In the interval, the beam retraces at the end of each line, and the vidicon is turned off by a "blanking" signal that consists of a pulse of intensity corresponding to a black signal and therefore invisible in the picture. This same interval, between scan lines, is employed in providing for synchronization, which is necessary for reproduction. The picture signal, fed to the receiver or monitor, will produce an image, the quality of reproduction being governed by the ability of the receiver to generate an exact replica of the scanning format of the transmitter vidicon.

In the case of the Electronic Scanner, the image is focused on the television transmitter vidicon by the konimeter microscope. The picture signal is fed simultaneously to the monitor and the data processor, the scaler control and the counter. An amplifier/analyser used with the counter eliminates "noise" appearing from scattered light and amplifies the pulses generated by particles so that they can be counted by the scaler.

The scaler control unit, employing synchronization pulses generated by the transmitter to recover and reshape the pulses in the picture signal into well-defined pulses, limits the count interval for each scan line and limits the counting to one picture (262½ horizontal scan lines) each time.

When an operator initiates the count cycle by depressing the "start" button on the scaler, the scaler sends a pulse to the electronic switch in the amplifier/analyzer that sets it in a ready state. The first scan permits the start of the count cycle and the second scan pulse, signifying the start of the second scan, closes the electronic switch, preventing repetitive counting. Thus, one scan comprises half a picture; the second scan is necessary to obtain the second half. In konimetry, dust concentrations are reported in particles per cubic centimetre (ppcc). The particles deposited on the glass slide represent the amount of dust contained in a 5-cc air sample. Thus, if the total number of particles counted in two full pictures or four scans was divided by a factor of 10, the result would be recorded directly in ppcc.

PRELIMINARY TESTS

When preliminary tests were started, it soon became evident that two variable controls in the amplifier/analyser circuits would affect the counts materially. Optimum setting of these controls would have to be found before a meaningful relationship between methods of counting could be determined. The two variables are the degree of attenuation of the signal to the unit and the threshold, or lower level, below which background or transmission noise is not counted. Background or transmission noise is not distinguishable from the signal generated by extremely fine dust particles.

A glass konimeter slide containing dust spots, taken some time previous during a routine survey, was used. The requirement was that the spots be of acceptable quality and varying density, with a minimum of contamination. The slide was washed with hot distilled water, which in turn was removed with 65 OP ethyl alcohol. The latter was burned off according to standard procedure.

A number of spots of varying concentration were counted with the Electronic Scanner at various attenuation and lower level settings. Background readings were taken after each count by adjustment of the microscope focus so that the video picture was out of focus. The gross spot count less the background was plotted on a graph (*Figure 3*).

The optimum response appeared to be at attenuation setting 5, lower level 250-260. All further tests were carried out at this attenuation 5, but the lower level varied from 250 to 340. Frequent checks revealed that background noise was caused by voltage fluctuation and radio frequency interference caused by large induction motors, etc. However, this interference could be minimized by varying the lower level settings to maintain a background count equivalent to 0-5 ppcc. The choice of attenuation setting 5 was important in this respect. A relatively small change in lower level below the 250 setting resulted in a sharp decrease in count, readily apparent by visual check on the monitor screen and the scaler count. In the opposite direction, a relatively large change in the setting resulted in a small increase in count.

In the attenuation 4 setting, the peak or maximum count was not as apparent and a large adjustment was required to effect small corrections. This was judged to be as undesirable as an attenuation 6 setting. Here a good peak is evident, but extremely small adjustments resulted in large corrections; small voltage fluctuations created wide fluctuations in background.

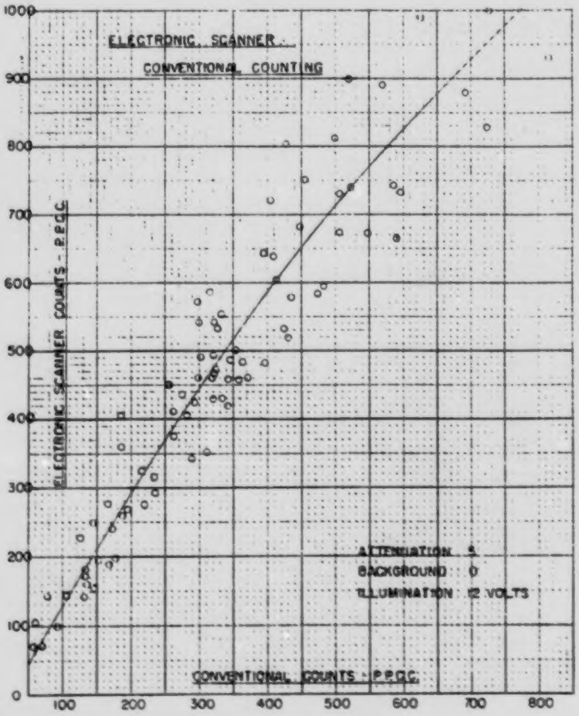

Figure 2.—Conventional Counting.

MICROSCOPE SUBSTAGE ILLUMINATION

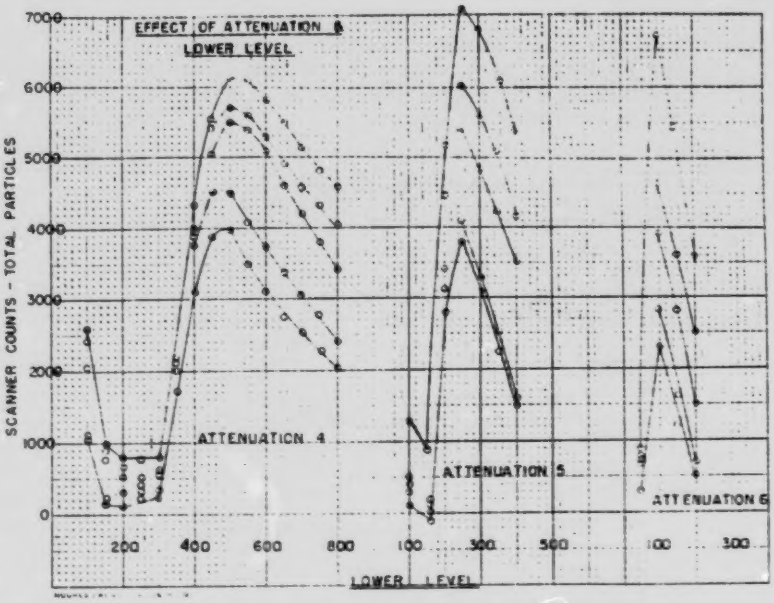

Figure 3.—Effect of Attenuation and Lower Level.

In the early configuration, one of the major sources of difficulty was the low level of illumination available. Earlier tests on microscopes revealed that an important factor in dark-field counting was the degree of contrast between the reflected light spot and the background. The original light source used, a transformer-powered substage lamp rated at a maximum of 8 volts, 15 watts, was found to be inadequate. It was felt that greater contrast, resulting in greater signal intensity, would result by the introduction of a larger darkstop or through the use of filters. The net result would be more accurate scanner counts.

The acquisition of a larger substage lamp, using a 12-volt, 60-watt light source, coupled with a larger darkstop did increase contrast. A comparison of counts using the scanner with counts obtained by conventional counting showed that increased congruency of counts was obtained. It is believed that increasing illumination coupled with the larger darkstop increased the intensity of the signal derived from dust particles considerably above that obtained from transmission "noises," thus facilitating separation of these signals.

ESTABLISHMENT OF COUNTING RELATIONSHIP

Once the tests establishing the optimum settings and light intensities were completed, the main objective was to establish a line or curve that would represent the relationship of the counts obtained with the Electronic Scanner with the counts obtained by conventional counting.

Konimeter slides containing spots, collected to fulfill the requirements of the *Semi-Annual Survey of Air Conditions*, were used to establish the relationship. The slides were treated in accordance with standard procedures as outlined in *Konimeter Dust Sampling as Practiced by the MAPAO Engineers — 1967*. Each spot was counted by two experienced observers, each centering and focusing the spot on separate microscopes. Counts were compared to agree within 5 per cent, and averaged.

The complete slide was counted on the Electronic Scanner, each spot carefully focused and centered on the monitor. The spots were recorded on a graph, plotting the average conventional count on the abscissa and the scanner counts on the ordinate. The best line drawn on the graph was taken to be the correlation curve.

The final field test was carried out basically to check the validity of the correlation curve. Data collected during this test served to indicate, at the same time, the most logical procedure to be used if the scanner were to be maintained at a central location on a continuing basis.

A second company, located in an entirely different mining camp, supplied konimeter slides for the test. In addition, ventilation personnel at that company treated, counted and stored the slides in a desiccator until a number of slides accumulated. These slides were scanned through a standard microscope to make sure that they were not contaminated in the interval between conventional and scanner counting. Scanner counts were converted to compare with conventional counts and entered on copies of work sheets or logs provided by the company. Random spots were counted by conventional means by the same observers.

On completion of the tests, the scanner counts, converted to compare with conventional counts, were summarized on forms used for the *Semi-Annual Survey of Air Conditions*. These results were compared with the summary of results submitted by the company.

FIELD TEST RESULTS

Examination of field results showed the Electronic Scanner results to be 11.5 per cent higher when compared to the mine survey count. The results were based on a total of 465 individual spot counts. Observer counts, checking random counts, showed that a wide discrepancy existed between counts done by an experienced MAPAO observer and those of the mine personnel. This discrepancy was in some instances in excess of 50 per cent. The correction of counting errors resulted in a normal deviation of counts on subsequent checks. The abnormal counting is, however, included in the over-all average.

Authoritative sources estimate that the variation in konimeter dust counting can vary by as much as 25 per cent, with experienced counters, when individuals center and focus the dust spots individually. Our experience shows that when comparison counts are made by observers with varying amounts of counting experience, and limiting the adjustment of the microscope to focusing only, this variation can be and is exceeded. The principal cause of the deviation appears to be observer bias.

Unfortunately, data were not compiled to check, with any degree of accuracy, the scanner's ability to reproduce counts. However, experienced operators find that counts can be obtained with less than 1 per cent deviation, providing that slide storage does not contribute any contamination.

THE MAPAO SCANNER PROGRAM

On completion of the tests, it was decided that konimeter slides submitted by Ontario mines would be counted with the Electronic Scanner. The Scanner would be set up at a central location, in this case the field offices of the Mines Accident Prevention Association of Ontario, and slides would be sent there for evaluation.

The successful evaluation of submitted slides depends on the quality of the samples submitted and the comparison of counts depends on the methods of sampling and slide treatment. For best results, it was decided that:

(1) the slide preparation and sampling be carried out according to standard practices established over the years;
(2) slides be given an initial treatment to remove carbonaceous material and "fix" the dust particles on the slide;
(4) slides be packaged and shipped for further treatment and counting at the central location; and
(4) slides be acid-treated, counted and returned by the Association, in most cases by return mail.

The program was initiated recently and results to date are encouraging. Random comparison counts indicate an over-all deviation of 2 per cent. This is much better than expected and deviation is not expected to exceed 15 per cent.

CONCLUSIONS

The program outlined above is in its initial stages. Changes are likely, but the over-all objective will always be the same — to give a rapid and unbiased assessment of conditions at working places as represented by the submitted sample, directly comparable to practices in the past.

The program was initiated to eliminate the long and tedious task of counting by eye. It will provide ventilation personnel with time for more constructive work to improve ventilation and dust control systems. It will, it is hoped, encourage the use of konimetry to assess the effect of changes, and routine sampling to establish over-all conditions will be improved by more frequent sampling.

ACKNOWLEDGMENTS

Much credit for the development of the Electronic Scanner is due to Dr. C. G. Stewart, Head, Medical Division, A.E.C.L., Chalk River, Dr. C. S. Gibson, former chief engineer and safety director, MAPAO, and G. R. Yourt, environmental consultant, Rio Algom Mines Ltd., Toronto, who, in early discussions with Dr. Eichholz, conceived and planned the project. Acknowledgment is also due to: the management and staff of the International Nickel Company, Rio Algom Mines Ltd. and the Federal Mines Branch (Elliot Lake) for assistance during test work; T. R. Flint for his continued interest, advice and technical service; and the Association's Subcommittee on Dust Control for technical advice and support.

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Section 2—Chapter 12

Determination of Respirable Quartz in Mine Air Using Personal Samplers and X-Ray Diffraction

by

G. Knight

Proceedings 18th Spectroscopy Symposium and Exposition
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Dosage du quartz inhalable dans l'air des mines à l'aide d'échantillonneurs personnels et de la diffraction des rayons X.

Résumé - L'étude fait partie d'un programme de recherche sur les techniques d'échantillonnage des poussières applicables dans les mines en roche dure qui est réalisé présentement au Canada. La technique et l'étalonnage comprennent, en premier lieu, une séparation des poussières inhalables dangereuses qui, à partir des poussières grossières déposées dans l'arbre bronchique tapissé de mucus, peuvent pénétrer dans la région alvéolaire des poumons et, en deuxième lieu, une évaluation de la composante quartz des poussières inhalables qui est particulièrement dangereuse. On donne une description de l'étalonnage de la technique dans un nuage de poussière de quartz pur produit dans la chambre de dépôt en laboratoire et on formule des commentaires concernant des échantillons prélevés dans des mines. On donne aussi les résultats de quelques essais préliminaires dans lesquels on a recours à la résolution énergétique plutôt qu'à la résolution angulaire pour le dosage du quartz par diffraction des rayons X.

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DETERMINATION OF RESPIRABLE QUARTZ IN MINE AIR USING PERSONAL SAMPLERS AND X-RAY DIFFRACTION

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It is apparent that, even after 30 years of dust control programs in Canada, there is still a health hazard to miners due to dust (1). Part of the failure of these programs may be attributed to poor correlation between the health hazard of the dust cloud and the dust index determined by the existing instrumentation.

This study forms a part of the program of research into dust sampling techniques for hard rock mines that is being undertaken in Canada. The technique and calibration described involve, firstly, a separation of the hazardous "respirable" dust that can penetrate to the alveolar region of the lungs from the coarser dust deposited in the mucous-swept bronchial tract and, secondly, an assessment of the particularly dangerous quartz component of the respirable dust. The technique combines the Casella (2) personal gravimetric sampler fitted with a cyclone size selector and the X-ray diffraction thin-layer quantitative-analysis technique previously developed for quartz by J. Leroux(3).

This report describes the calibration of the technique in a cloud of pure quartz dust generated in the laboratory dust chamber (4) and comments on samples taken in mines. Also given are the results of some preliminary tests using energy resolution instead of angle resolution for quantitative X-ray diffraction determination of quartz.

EXPERIMENTAL TECHNIQUES

Choice of Filter: The 5-µm pore size silver membrane filter was chosen because this material gives a low background at the main quartz diffraction lines, is non-hygroscopic, is mechanically strong, and can be ashed without change in weight. The low-resistance coarse pore size has to be used to permit the design airflow with the battery-powered personal sampler.

Dust Cloud: A quartz dust cloud was generated in the laboratory dust chamber using a twin-jet fluid energy mill.

Dust Sampling: Samples were taken simultaneously with four Casella personal samplers (2 ℓ/min) and one Casella Hexhlett sampler (50 ℓ/min) for various lengths of time. For the short sampling times, the quartz collected on the personal samplers could not be weighed accurately and the quantity was calculated by comparison with the Hexhlett.

X-Ray Diffraction Equipment: This was supplied by Philips and consisted of an ultrastable generator, copper and molybdenum target tubes, vertical goniometer, automatic sample changer, graphite-crystal diffracted-beam monochromator, pulse height analyser, step scanner, and teletype printout.

RESULTS

Intensity measurements were made on the 101 quartz line using both copper and molybdenum Ka radiations. The peak heights were determined as the average of the 5 highest steps less the background, and the peak areas were determined by summing all steps significantly above the background and subtracting the background. Figure 1 shows a linear plot of X-ray intensity (peak height) against mass of quartz on the sample.

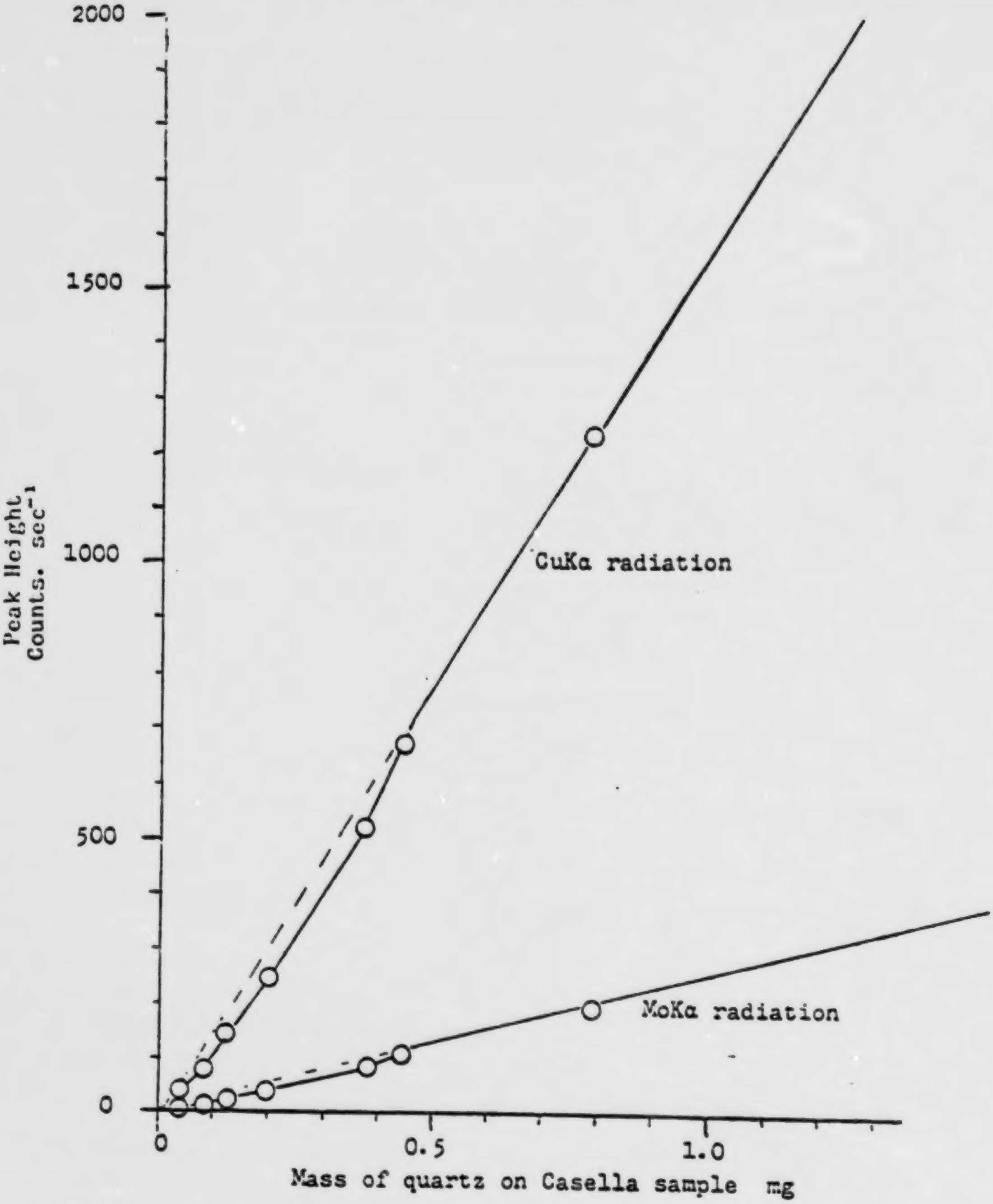

FIGURE 1: Quartz Calibration of X-Ray with Casella Samples

Figure 2 shows the ratio of intensity (peak height and area) to mass on a logarithmic scale plotted against the surface density of quartz on the filters.

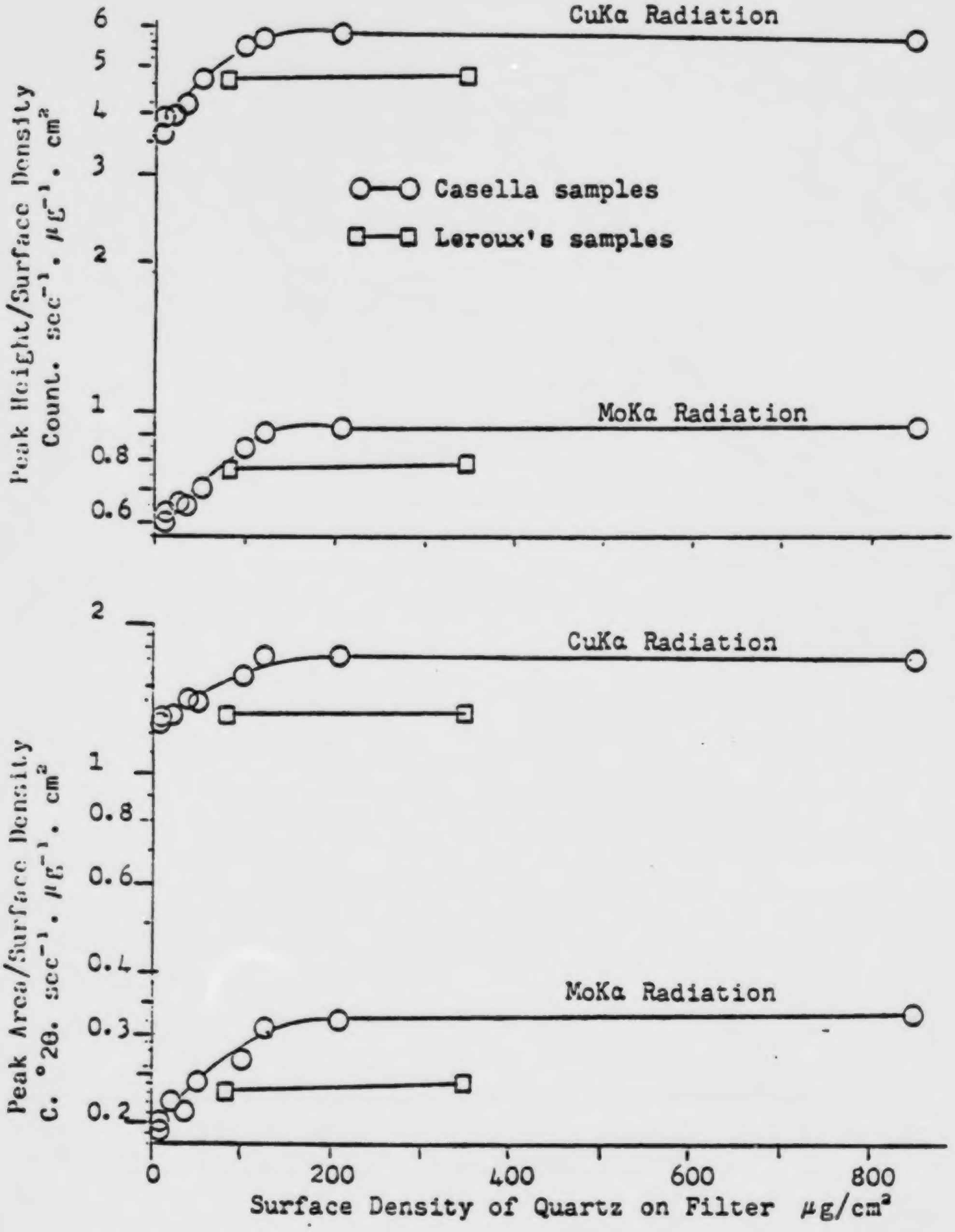

FIGURE 2: Quartz Calibration of X-Ray with Casella Samples and with Leroux's Samples

Also shown on this graph are some results on samples prepared by a different technique (5). It can be seen that there are three important factors:

1. CuKa radiation gives a counting rate about six times greater than MoKa radiation with only a slight increase in background;
2. there is a drop in the ratio of X-ray intensity to mass at low surface densities of quartz; this is apparently due to penetration of the finer quartz dust into or through the pores of the silver membrane;
3. there is an as yet unexplained difference between the two methods of preparing standard quartz samples.

DISCUSSION

Application to Field Samples

Samples taken in a number of mines were examined. In analysing these, it was assumed that the penetration of quartz into the filter depended on the total mass of dust collected rather than on that of the quartz alone.

On these field samples, peaks were detected corresponding to as low as 0.005 mg of quartz which is approximately one tenth of the threshold limit value (6) for a shift period sample.

Interference by other minerals was noticed in some cases, and checks were made using other quartz lines. This aspect of the research is now receiving our major attention. The copper Ka radiation gives a resolution twice that of molybdenum and is desirable to minimise interference.

Absorption

This technique assumes that the layer of dust is thin enough for corrections for absorption to be negligible. Iron pyrite is the most common mineral with high absorption for copper Ka radiation and some experiments showed that 300 $\mu g/cm^2$ of pyrite will reduce the diffracted X-ray intensity by about 25%, which is probably about the permissible limit of error. This may be a significant factor in a few mines.

ENERGY RESOLUTION

During the course of this work an opportunity was found, courtesy of Radionics Ltd., to test an Ortec, 6-mm, high-resolution, lithium-drifted-silicon detector. The comparison between normal 'angle resolution' diffractometry and energy resolution at a fixed angle (7) is shown in Table 1 for three settings:

1, $\theta = 19.05^\circ$ CuKa coinciding with 1st Ag diffraction line,
2, $\theta = 8.8^\circ$ AgKa coinciding with 1st Ag diffraction line,
3, $\theta = 3.0^\circ$ all quartz diffraction lines at energies higher than AgKβ.

TABLE I

COMPARISON OF ANGLE AND ENERGY RESOLUTION

Quartz Line	Angle Resolution		Energy Resolution			
			Set up 1	Set up 2		Set up 3
	101	112	101	101	112	101
Diffraction Angle °2θ	26.64	50.12	38.1	13.6		6.0
Diverging Slit	1.0	2.0	1.0	0.5		0.25
Scatter Slit °2θ	(1)		1.0	0.5		0.25
Receiving Slit mm	0.156	0.156	0.156	0.156 (2)		0.156
Detector	Scintillation					
Analysis	PHA		Multi-Channel Analyser			
Scanning	0.04°2θ Steps		1024 channels, 0.05 keV/channel			
Channel Width = d A	0.005	0.0014	0.03	0.011	0.0033	0.005
Width at 1/2 height = d A	0.025	0.009	0.22	0.085	0.03	0.11
Peak-background cps	2700.	175.	2.56	1.55	0.06	0.175
Area cps . d	68.	1.6	0.56	0.132	0.0018	0.019
Peak-back background	14.3	1.95	0.46	11.4	2.1	21.

Footnotes:

(1) Graphite monochromator is used; eliminates interference by fluorescence.

(2) Ortec 6mm dia, 3-mm sensitive-depth, lithium-drifted silicon.

The results obtained show that the diffraction lines are broader with energy resolution than with angle resolution and that counting rates are lower. However, the set up could probably be improved to give equal counting times if more than two lines need to be examined. Possibly with on-line computer processing, angle resolution of a quartz line and a check for interference on other lines, using integrated energy resolution over the number of angle steps required, would be a quick method.

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Section 2—Chapter 13

The Determination of Quartz in Dusts by Infrared Spectroscopy

by

A.H. Gillieson and D.M. Farrell

Canadian Spectroscopy 16 pp21-26 (1971)

The Determination of Quartz in Dusts By Infrared Spectroscopy

by A. H. Gillieson* and D. M. Farrell**

Résumé

Le quartz Alpha a été déterminé à un niveau de un dixième de milligramme après l'avoir recueilli sur un filtre de chlorure de polyvinylidène ("Saran") à l'aide de sa bande d'absorption caractéristique à une longueur d'onde de 12.5 microns. La limite de détection, dans les présentes conditions, a été estimée à un vingtième de milligramme. Les possibilités d'interférence, due à la présence de feldphate, de mica et de pyrite, ont été examinées. D'après les spectres trouvés dans la littérature, la hornblende, la kaolinite et la montmorillonite pourraient aussi être cause d'interférences.

En utilisant un détecteur infra-rouge sélectif et des filtres combinés de chlorure de polyvinylidène et de "Irtran 2" (sulfure de zinc) on pourrait construire un appareil infra-rouge simple pour la détermination du quartz alpha dans la poussière.

Abstract

Alpha-quartz has been determined down to one tenth of a milligram when collected on a polyvinylidene chloride ("Saran") filter, by the absorption of its characteristic peak at a wavelength of 12.5 microns. It was estimated that the limit of detection under the conditions used, was one twentieth of a milligram. Possible interferences from feldspar, mica, and pyrite have been examined. According to the spectra recorded in the literature, hornblende, kaolinite and montmorillonite might also interfere. By the use of a selective infrared detector and composite filters of polyvinylidene chloride and "Irtran 2" (zinc sulphide) it is suggested that a simple non-dispersion infrared analyser for the determination of alpha-quartz dusts might be devised.

Introduction

In February 1967 a number of air sampler filters were examined by infrared spectroscopy at the request of the Mining Research Division, to determine whether any of the filter materials had adequate transparency at 12.5 microns, the wavelength of the characteristic peak of alpha-quartz. One filter, made of polyvinylidene chloride ("Saran") had the required transparency. Known weights of quartz were deposited on a number of these Saran filters, and the infrared spectra of these filters were recorded on a Beckman IR-12 spectrometer. A composite of the resulting spectra

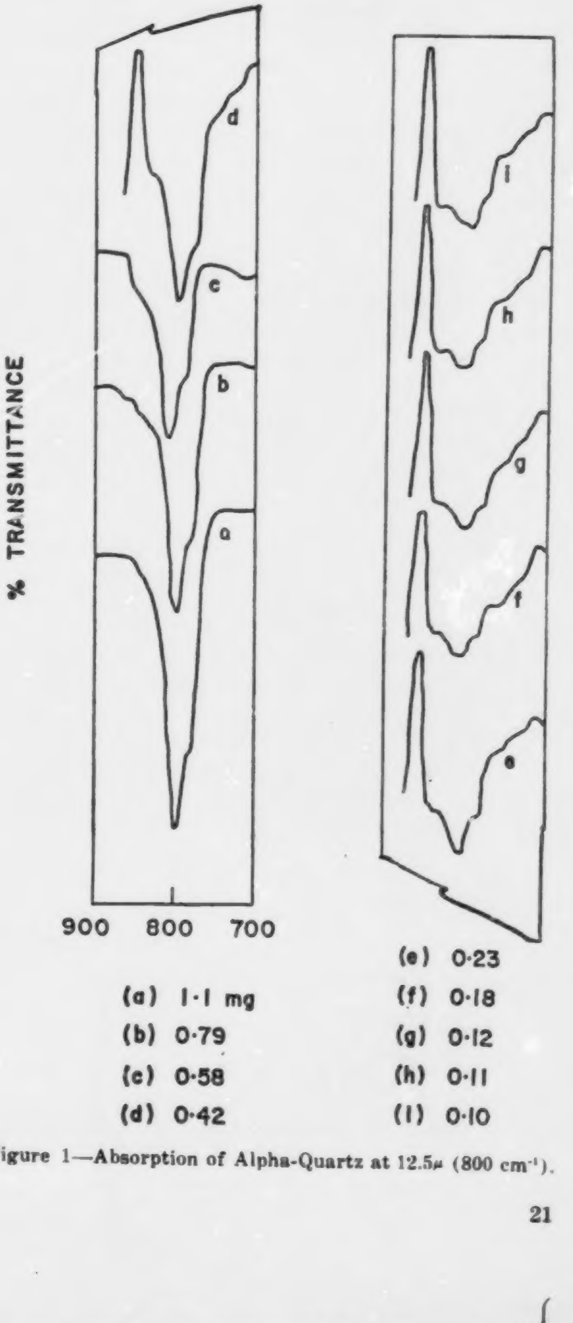

Figure 1—Absorption of Alpha-Quartz at 12.5μ (800 cm⁻¹).

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in the wavelength neighbourhood of 12.5 microns is shown in Figure 1 and a plot of the absorption of the 12.5 quartz peak versus weight of quartz on the filter is shown in Figure 2. The data from which the absorption-weight graph was constructed are listed in Table 1.

Non-Dispersive Infrared Analysis for Quartz

The brief preliminary investigation described indicated that it was feasible to determine α-quartz on polyvinylidene filters down to an amount of 0.05 mg.

In March 1969, the question was put whether a relatively inexpensive simple analytical method for quartz determination by infrared were feasible and it was suggested that non-dispersive infrared analysis might serve.

Gas analysers based on this principle have been commercially available for 25 years. In essence. they consist of an infrared source, a rotating "chopping disc", a sample and reference chamber, and a double-celled detector. The infrared radiation from the source is passed alternately through the sample and the reference chambers and into the "sample" detector cell or into the "reference" cell. The detector cells each contain an equal and appropriate amount of the gas to be determined, and are divided by a gas tight diaphragm. One side of the diaphragm is metallized and forms, with a fixed plate mounted close to it, a variable-capacity condenser which is part of the electronic measuring circuit.

If the sample and reference chambers contain either no gas or equal amounts of the same gas present in the detector cells, the amount of infrared radiation falling alternately on the cells is equal, the absorption of the radiation in the two cells and the resultant heatings of the gas in the two detector cells are of the same amount, and there is neither difference of pressure on the two sides of the flexible diaphragm, nor movement of the diaphragm to alter the capacity in the electronic circuit.

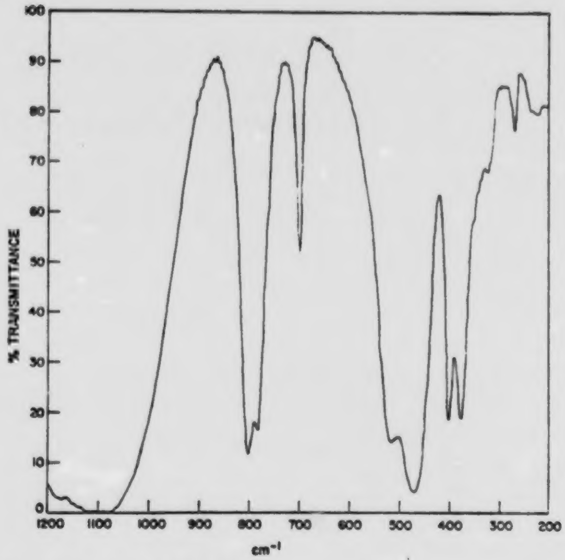

Figure 2—Alpha-Quartz.

If, for example, the sample chamber contains more of the gas to be measured than the reference chamber, then more of the infrared radiation will be absorbed in the sample chamber and less will be absorbed by the gas in the corresponding detector cell. The gas pressure in the "sample" detector cell will be lower than that in the "reference" detector cell, and the diaphragm will move toward the "sample" detector.

Because the gas in the detector cell absorbs at only the wavelengths at which it emits radiation, it is a selective detector for these specific wavelengths. Even if other gases absorb at some of these wavelengths provided that their amount remains fixed, their absorption can be compensated for by introducing the same concentration into the reference chamber.

Since no radiation is wasted by grating dispersion or prism absorption and, because of the very simple optics, a minimum is lost by absorption in lenses or windows, these non-dispersive infrared gas analysers are relatively sensitive. Their sensitivity is also improved by the fact that they

TABLE 1.

Absorption of Alpha-Quartz (12.5 peak) vs Weight of Quartz on Filter

Sample No.	3	4	9	2	10	12	14	15	17
Wt. quartz (mg)	0.10	0.11	0.12	0.18	0.23	0.42	0.58	0.79	1.10
Peak (%T)	82.0	80.0	84.0	76.7	71.8	70.6	62.7	51.5	39.5
Background (%T)	90.3	87.7	90.4	86.0	84.0	94.0	84.2	82.7	79.9
Quartz absorption	0.042	0.040	0.032	0.50	0.068	0.124	0.128	0.206	0.306

The best straight line fitting the values in the table is:
Absorption = 0.25 (mg of quartz) + 0.00665 and the estimated limit of detection is 0.05 mg of quartz.

absorb at all the wavelengths, at which the gas absorbs, instead of at one selected wavelength, as is the case in dispersive analysis. These robust, simple, and sensitive gas analysers have over years of use proved the validity and reliability of the method.

Although quartz is not a gas, it was considered that non-dispersive infrared analysis might be feasible if there were available a detector selective only for the wavelengths at which quartz absorbs. Ideally, the best detector would be alpha-quartz itself.

This goal is possible if use is made of the temperature coefficient of the piezo-electric effect. If a sheet made from a quartz crystal forms the dielectric in a capacitor and if such a capacitor forms part of a tube or transistor oscillator circuit, the quartz sheet will constrain the oscillation frequency of the circuit within a very narrow range which is characteristic of the way the sheet was cut from the crystal, of the dimensions and of the shape of the sheet.

For this very accurate oscillator frequency control, the "cut" of the sheet is made so that the temperature coefficient of the characteristic frequency is a minimum or zero over as wide a temperature range as possible.

It is possible, however, to cut the sheet from the quartz crystal so that the temperature coefficient of the frequency is a maximum and use has been made of this type of "cut" in a commercial "Linear Quartz Thermometer", developed and marketed by Hewlett-Packard, that is sensitive to a temperature change of 1/10,000°C between —40°C and +230°C(1).

Because the infrared radiation of 12.5μ is heat radiation, it is proposed to modify this commercial "electronic" thermometer to serve as detector for the radiation. This would be done by removing the central portions of the deposited gold electrode from both sides of the circular, quarter-inch-diameter quartz wafer and by focusing the heat radiation on this clear spot on the sensor.

The clear quartz sensor will preferentially absorb heat radiation of the wavelength of its own absorption and will thus act as a specific detector of such radiation.

If such a quartz detector is irradiated with infrared radiation, say, from a platinum filament heated to 1300°C in air, it will absorb at the wavelengths specific to quartz and will rapidly reach heat equilibrium with its surroundings. The frequency of the associated oscillator will show a change linearly proportional to the temperature change of the crystal.

If, now, a quartz sheet is inserted between the infrared source and the detector, it will absorb some of the specific "quartz" radiation and less will fall on the detector. The resulting change in temperature of the detector and in the oscillator frequency will be proportional to the thickness (amount) of the quartz sheet through which the beam has to pass.

With such a device, we have in principle a non-dispersive infrared analyser specific for alpha-quartz, but, first, we have to establish two aspects of its practical feasibility:—

(i) which of the absorption peaks of alpha-quartz is most free from interference from absorption peaks of related minerals such as silicates and minerals associated with quartz in rocks;

(ii) the sensitivity and the limit of detection of the device.

Mineral Interferences(2)

The minerals which would be expected to interfere are:—

Olivines, Pyroxenes, Amphiboles, Micas, Feldspars, Clays.

The infrared absorption spectrum of alpha-quartz has been studied and interpreted by B. D. Saksena, 1940(3) and by E. R. Lippincott, 1958(4); and between 200 and 1200 cm^{-1} is shown in Figure 2.

The peaks shown have the frequencies and assignments given in Table 2.

TABLE 2

Assignments, Wavelengths and Frequencies of Alpha-Quartz Spectrum

Assignments	Wavelengths (μ)	Frequencies (cm^{-1})
Distortion	37.7	265
Si-O Bend	25.2	397
Si-O Bend	21.3	470
Si-O Bend	19.5	513
Si-Si Stretch	14.3	698
Si-Si Stretch	12.8	780
Si-Si Stretch	12.5	800
Si-O Stretch	9.1	1097

The most suitable absorption peak and that used in preliminary experiments is the Si-Si stretch at 12.5μ (800 cm^{-1}). Table 3 lists the wavelengths of the absorption peaks, nearest this wavelength and most likely to interfere, belonging to the previously mentioned minerals.

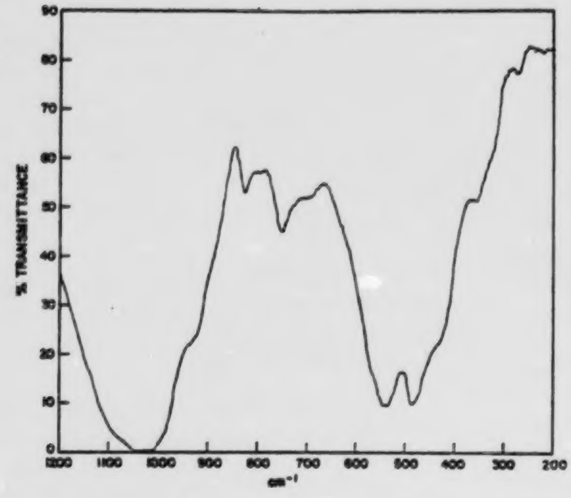

Figure 3—Mica.

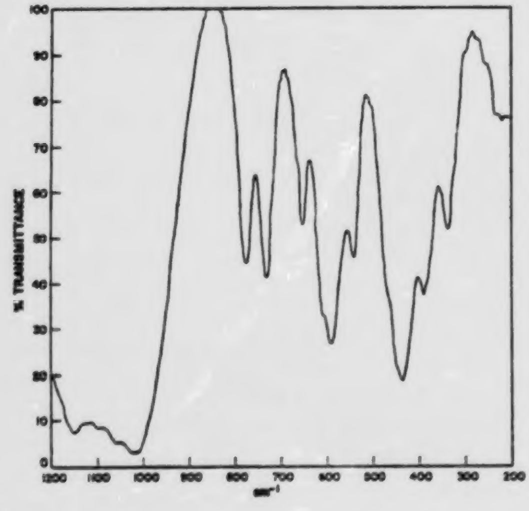

Figure 4—Feldspar.

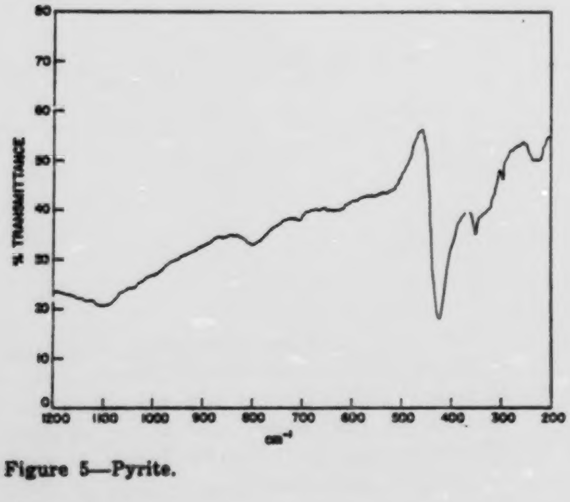

Figure 5—Pyrite.

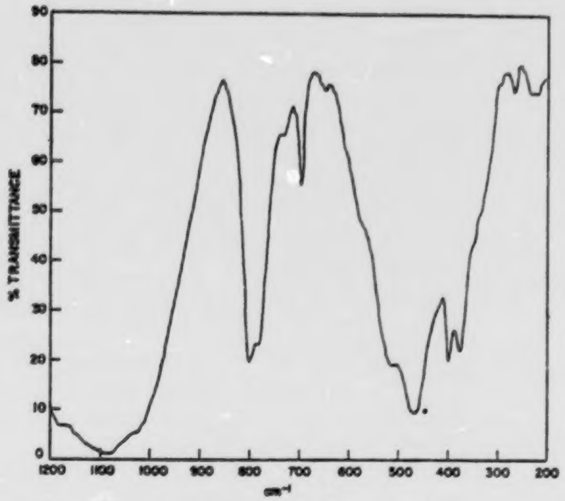

Figure 6—Nordic Ore (Elliot Lake).

As is evident, of the potentially interfering minerals previously listed, only the micas, feldspars, and clays need be considered.

It was, however, considered advisable to confirm these literature indications by experiment; and we therefore obtained samples of a typical Elliot Lake ore ("Nordic"), a mica, a feldspar, and a pyrite. The spectra of these four materials are shown in Figures 3 to 6. Each of these materials and the alpha-quartz (Fig. 2) constituted 0.5% of pellets made up with caesium bromide and were recorded in transmission. Because all the spectra have been recorded with the same amount of each mineral, they show the maximum (and unachievable) interference of one mineral with another.

Although the "Nordic" ore is known from mineralogical examination to contain mica, feldspar, and pyrite, it is clear, from comparison of its spectrum with those of the individual minerals, that its main constituent is quartz. A study of Figure 8 which shows the position of the peaks of all the constituent minerals makes this even clearer.

Further examination of this composite record indicates that, of all the alpha-quartz peaks, the chosen one, at 12.5μ, is the most free from interference — only minor peaks of 100 per cent mica and feldspar and a weak broad absorption from 100 per cent pyrite being involved.

Because of the large amount of interference on the quartz peaks other than at 12.5μ, it is essential to prevent them having any effect on the quartz detector; and this has to be achieved by selective filters which will pass only a narrow wavelength range on either side of 12.5μ.

TABLE 3.
Infrared Absorption of Quartz and of Related Minerals

Mineral	Wavelength in microns						
	8	9	10	11	12	13	14
α-Quartz	8.5	9.2	10.95		12.5, 12.8		14.4
Amphiboles		9.0 — 9.8	10.1 — 10.8		12.8(1)	13.1	[illegible]
Feldspars	8.7 — 8.8	9.1 — 9.9	10.0 — 10.9		12.2, 12.7(2)	13.1 — 13.8	14.6
Micas		9.4 — 9.7	10.0, 10.3	11.0	12.1, 12.5(3) 12.8	13.1	14.8
Olivine			10.0, 10.5	11.2, 11.9		13.1	
Pyroxene		9.4 — 9.8	10.4, 10.9	11.5			
Clays	8.9 — 9.0	9.6 — 9.9	10.7	11.0	12.1, 12.5, 12.6, 12.8	13.3	14.5

(1) Hornblende only; (2) albite and oligoclase; (3) muscovite only

In the preliminary work, it was found that the air filter made of polyvinylidene chloride ("Saran") had a transmission "window" in the desired range; and is therefore a suitable choice as a component of the selective filter. By combining four layers of "Saran" sheet (as used in the household), an optical filter was available which had negligible transmission over a large part of the range wanted and a window of 70% transmission at 12.5μ. Some radiation is passed beyond 13.5μ; therefore, an additional filter of "Irtran-2" (zinc sulphide), which is transparent up to 14μ but absorbs strongly at longer wavelengths, is suggested.

The resulting composite filter need have little thickness and would conveniently consist of a sheet of "Irtran-2" covered on one side with one sheet of "Saran" and on the other with two sheets of "Saran" — the air filter used for collecting the dust sample provides the fourth "Saran" sheet.

Examination of the composite spectrum (Figure 8) shows that the "Saran" filter will remove interference from the Si-O stretch absorption peaks of mica and feldspar between 1000 and 1100 cm^{-1} (9.1-10μ) and, with the addition of the "Irtran-2" filter, will remove interference between 780 and 200 cm^{-1} (12.8-50μ).

There remain three peaks which might interfere — a minor mica peak at 829 cm^{-1} (12μ), a minor feldspar peak at 777 cm^{-1} (12.8μ), and a broad pyrite peak at 800 cm^{-1} (12.5μ). The "pyrite" peak is undoubtedly due to quartz in the pyrite because records of other pyrites, known to be free from quartz impurity, do not display this absorption peak. Interference from the minerals associated with the "Nordic" ore is thus limited to mica and feldspar. It is to be noted, however,

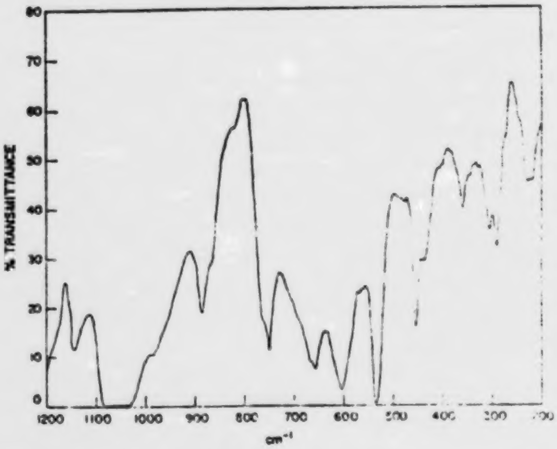

Figure 7—Polyvinylidene Chloride.

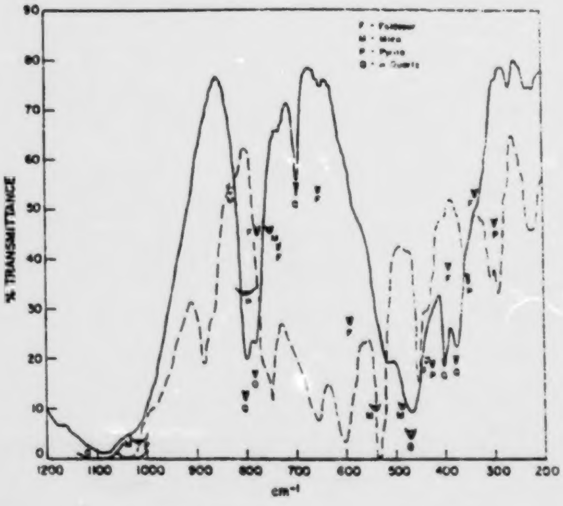

Figure 8—Composite Spectrum.

that the peaks compared are derived from 100 per cent of each mineral and that the amounts normally present in this ore are much less, being between 5 and 20 per cent. The resulting interference would in consequence be much less; and in proof of this view, in the spectrum of "Nordic" ore, the 12μ mica peak appears as a hardly observable inflection on the short-wavelength side of the 12.5μ quartz peak and no effect of the feldspar peak can be observed.

Optical Design of "Silica-Meter"

The instrument can be designed either as a single-beam or as a double-beam analyser. In the first case, the power supply for the infrared source must have very good short-term and long-term stability and constancy whereas, in the second, these requirements do not arise and a much simpler and cheaper power supply can be used.

The double-beam arrangement is preferred, in spite of the small additional complexity, not only for the reason presented in the preceding paragraph but because it enables the absorption of the "Saran" and "Irtran-2" filters to be balanced out. The frequency difference between the sample and the reference beams would then be a measure of the absorption due to alpha-quartz (silica) in the sample.

Assuming the platinum strip (10 mm long, 1 mm wide) infrared source is a perfect blackbody, it can be calculated that, at a temperature of 1200°C, it will emit 3.355 x 10^8 ergs/cm^2/sec. If a concave mirror of 5-cm dia at 6-cm distance is used to focus this radiation on the detector, the latter will receive 1.455 x 10^6 ergs sec. For 1°C rise in temperature, the detector must absorb 1.326 x 10^7 ergs and, therefore, the detector will require 9.1 sec to rise 1°C. Such a theoretical response time is adequate; in fact, a 10-sec response time is quoted by Hewlett-Packard for their "Linear Quartz Thermometer".

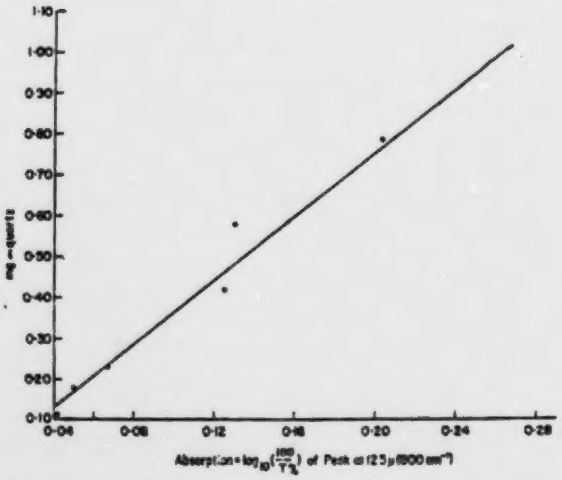

Figure 9—Absorption by Alpha-Quartz at 12.5-Micron Wavelength.

Practical Testing

It is proposed to construct a simple prototype in order to find out the limit of detection and the precision of analysis for alpha-quartz in mine-dust.

This will consist of a 10 x 1-mm platinum strip run at 1200°C in air. The infrared radiation from it will be focused by two front-surface aluminized concave mirrors on to the two sensors of the "Linear Quartz Thermometer", modified as previously described. In front of each sensor there will be a composite filter of "Saran" and "Irtran-2" and a sample holder to take, in the one case, the sample air-filter and, in, the other case, a blank air-filter.

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Section 2—Chapter 14

Laboratory Calibration of a Technique for Determination of Respirable Quartz in Mine Air

by

G. Knight, W. Stefanich and G. Ireland

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33(7) pp469-75 (1972)

Étalonnage en laboratoire d'une technique de dosage du quartz inhalable dans l'atmosphère des mines

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On a examiné par diffraction des rayons X en employant les rayonnements Kα émis par le molybdène et le cuivre et un procédé de balayage par points, les échantillons prélevés avec un échantillonneur portatif Casella de poussières inhalables, dans une nuée de poussières de quartz pur émise dans une chambre à poussières expérimentale. On a effectué un étalonnage de ce système avec des quantités de poussières inhalables déposées sur le filtre, comprise entre 0,04 et 3 mg. On a observé une diminution des facteurs liant la hauteur des crêtes ou l'aire des crêtes à la masse de quartz lorsque les quantités de quartz sont faibles, sans doute en raison de l'effet de pénétration dans la membrane d'argent plutôt grossière que l'on a utilisée (calibre des pores 5 µm), et de l'effet d'écran causé par la rugosité de la membrane d'argent. On a aussi pratiqué des étalonnages avec des échantillons préparés selon la technique de Leroux d'élutriation et de collecte sur un filtre. Ainsi, les intensités des rayonnements X étaient de 25 % inférieures à celles émises par les échantillons préparés dans la chambre à poussières. On a mis à l'épreuve cette technique dans certaines mines ontariennes avec fouille au rocher, et dans des mines de charbon de Nouvelle-Écosse. Cette technique est assez sensible pour que l'on puisse déceler des concentrations de poussières inhalables de quartz de 0,01 mg/m^3 dans des échantillons recueillis durant un poste de travail. Toutefois, on a noté des interférences dues à la présence de mica dans un certain nombre d'échantillons.

Laboratory Calibration of a Technique for Determination of Respirable Quartz in Mine Air

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Samples taken by a Casella personal respirable dust sampler in a cloud of pure quartz dust in the laboratory dust chamber were examined by x-ray diffraction using molybdenum and copper Kα radiations with step scanning. A calibration of this system was obtained with respirable dust quantities on the filter of 0.04 to 3 mg. There was a decrease in the factors relating peak height or peak area to mass of quartz at low quantities of quartz, presumably due partly to penetration into the rather coarse (5-μm pore size) silver membrane used and to shadowing by the roughness of the silver membrane. Calibrations were also performed with samples prepared by Leroux's technique of elutriation and collection on a filter. These resulted in x-ray intensities 25% lower than those of the samples prepared in the dust chamber. This technique was tested in some Ontario hard rock mines and in Nova Scotia coal mines. The technique is sensitive enough to detect respirable quartz dust concentrations of 0.01 mg/m^3 on shift period samples. However, interference from mica has been found in a number of samples.

Introduction

It is apparent that, even after 30 years of dust control programs in Canada, there is still a health hazard to miners due to dust.[1] Part of the failure of these dust control programs may be attributed to poor correlation between the health hazard of the dust cloud and the dust index determined by the existing instrumentation.

This study forms a part of the program of research into dust sampling techniques for hard rock mines that is being undertaken in Canada. The technique described and calibrated in this report involves, first, a separation of the hazardous "respirable" dust that can penetrate to the alveolar region of the lungs from the coarser dust deposited in the mucus-swept bronchial tract and, second, an assessment of the particularly dangerous quartz component of the respirable dust. The technique combines the Casella personal gravimetric sampler (C. F. Casella and Co., Ltd., London, England) fitted with a cyclone size selector and the x-ray diffraction thin-layer quantitative analysis technique previously developed for quartz by Leroux.[2]

This report describes the calibration of the technique in a cloud of pure quartz dust generated in the laboratory dust chamber[3] and comments on samples taken in mines.

Because absorption by iron-rich samples may give rise to error when copper Kα radiation is used, calibrations were also carried out for pyrite to determine reasonable limits and the extent of corrections required by absorption.

Experimental Techniques

Dust Sampling Equipment

The Casella personal-size selecting gravimetric dust sampler (Ref T13040) was chosen as the most suitable of the personal-size selecting samplers available on the market because (1) the filter holder takes a 1-inch-diameter filter which is of a suitable size for direct insertion into the x-ray beam, and (2) the mass of respirable dust collected is the highest.

Dr. Leroux[2] recommended the use of a silver membrane (0.8-μm pore size) filter as a carrier for the x-ray analysis of quartz. However, to permit the passage of the required volume of air through a 1-inch filter with the chosen self-contained battery-powered sampler, it is necessary to use a lower-resistance filter. A larger-pore-size (5-μm) silver membrane has been chosen as a compromise. This filter has been tested as more than 99% efficient on weighable quantities of respirable dust. However, it was appreciated that a filter as coarse as this might not be an efficient collector for the finest respirable dust particles until a dust bed has built up on the surface. The dust is collected on a circle close to 22 mm in diameter, and in calculating the dust density per unit area, 3.8 cm^2 has been used for its area.

Preparation of Pure Quartz Samples in the Laboratory Dust Chamber

To calibrate the technique of determining respirable quartz in air down to the threshold limit value of 0.1 mg/m^3 on shift period samples, it was necessary to prepare samples with as little as 0.05 mg of quartz. This quantity could not be weighed sufficiently accurately, and it was necessary to determine the quantities of dust on the filters indirectly.

A quartz dust cloud was prepared by continuous dispersion of Ottawa (Illinois) silica sand with a twin-jet fluid energy mill into clean air in the laboratory dust chamber. Samples were taken with four Casella personal samplers (at 1.9 to 2.0 liters/min) and one Casella Hexhlett sampler (at 50 liters/min) for various periods from 1 to 90 minutes. The filters from all the samplers in the longer runs were weighed, and the ratios between the masses collected by the personal samplers and those by the Hexhlett were determined. Then, on the short runs, the masses of respirable dust collected by the Hexhlett were weighed, and those on the personal samplers were calculated from these ratios.

The mass of quartz on the filters ranged from 0.04 to 3.3 mg, equivalent to a surface density of 10 to 850 $\mu g/cm^2$.

Preparation of Pure Quartz and Pyrite Samples by Leroux's Technique

In this method[4] pure dust samples are finely ground and dispersed into a high-velocity airstream; this is slowed down, and elutriation occurs prior to collection on a 37-mm-diameter silver membrane filter. The samples used in this study were prepared by Dr. Machacek[5] on Dr. Leroux's apparatus.

The filters had been cut in four and were stuck on glass backing plates.

X-Ray Diffraction Equipment

Philips x-ray equipment, in particular the following components, is used: (1) an ultrastable generator—repeat peak heights are reproducible to a few percent over periods of weeks as long as no adjustments are made to other components, (2) copper or molybdenum x-ray tubes, (3) vertical goniometer, (4) automatic sample changer, (5) step-scanning facility, (6) graphite crystal diffracted beam monochromator—eliminates high background due to fluorescence, (7) scintillation detector, (8) pulse height analyzer, (9) timer scaler, (10) rate meter and chart recorder, and (11) teletype printer and paper tape puncher.

Preliminary Studies and Setup for X-Ray Diffraction

Preliminary studies were carried out to determine the optimum operating technique for this equipment. In particular, the effects of slit and step sizes were examined by using the diffracted beam monochromator, step scanning, and printout. The results obtained were as follows:

> *Diverging Slit Width.* Using a beam larger than the sample decreased the signal-to-noise ratio. Samples were run at the largest slit width that did not extend the beam beyond the sample (½° and 1°, respectively, for molybdenum and copper radiation on the quartz and pyrite lines).
>
> *Receiving Slit Width.* The count rate on a peak increased almost linearly with width up to 0.25 mm; at larger slit widths the rate of increase of count rate diminished rapidly. A

TABLE I

Calibrations of Quartz Samples (101 line) for Copper and Molybdenum Kα Radiation

Mass of Quartz ($\mu g/cm^2$)	Peak Height (counts sec^{-1})		Peak Area (counts °2θ sec^{-1})		Signal/Noise Ratio	
	Cu	Mo	Cu	Mo	Cu	Mo
Samples collected by Casella personal sampler						
842	4700	774	1430	280	73	9.4
208	1198	194	357	66	28	3.4
121	690	110	210	37.4	17	2.3
99	545	83	156	26.4	14	1.6
52	244	36.5	72	12.6	6.5	0.8
33	137	21.4	47	7.0	4.3	0.5
22	88	14.6	29	4.6	2.3	0.45
10.5	41	6.6	13.4	2.0	1.1	0.17
10.5	39	6.3	13.6	2.1	1.2	0.16
Samples prepared by Leroux's technique						
353	1650	276	468	84	32	3.5
83	382	63	107	19	9.6	1.0

slit width of 0.25 mm corresponds to 0.08° 2θ. The receiving width used has been the next width available above the corresponding step-scan interval.

Step-Scan Interval. At step-scanning intervals above 0.08° 2θ, the repeatability of peak height and area measurements as well as resolution between peaks has diminished markedly. All measurements have been made with a step-scan interval of 0.04° 2θ, which is the next available size.

X-Ray Wavelength. Copper radiation as compared to molybdenum improved resolution by a factor of about 2, increased intensity (count rate) on peaks by a factor of over 5, and had close to the same background. Results for both copper and molybdenum Kα radiations are given.

Improved reproducibility of peak heaight. This was obtained by summing more than one step. Five 0.04° 2θ steps (approximately the half-width of the peak) seemed the best measure and is used throughout.

Counting Period. A 20-second counting period on each step has been used in all this work except for some of the field samples that contained very little quartz.

Mounting Techniques. To hold 1-inch-diameter silver membrane filters, a 1-inch-diameter 0.005-inch deep well was turned in the sample holders supplied with the automatic sample changer. The samples were stuck down into these wells with a small amount of petroleum jelly. Checks on a microscope showed that the samples, unless distorted, were within 0.05 mm of being flat.

Results

Calibrations of Quartz Samples

Intensity measurements were made on the 101 quartz peak of samples collected by personal samplers in a pure quartz dust cloud using both copper and molybdenum Kα radiations. The results obtained are given in Table I and are shown plotted in Figures 1 and 2 with results on samples prepared by Leroux's technique.[4] Figure 1 shows a plot of peak height against mass of quartz using a linear scale, and Figure 2 shows the ratios of the peak height or area to the mass of quartz on the filter plotted against the mass of quartz on a logarithmic and linear scale, respectively. The logarithmic scale was chosen so that the shapes of the curves could be directly compared with one another.

The results obtained show that the ratio of x-ray intensity to calculated (from the mass of the 50-liter/min Hexhlett samples) mass of samples collected by the personal samplers decreases markedly for small samples. This is pre-

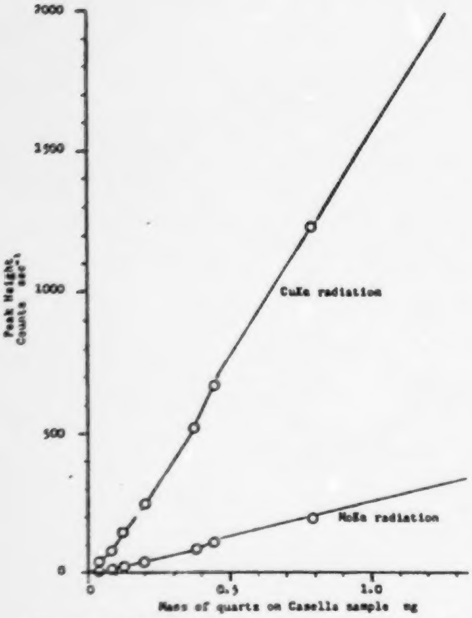

Figure 1. Quartz calibration of x-ray with Casella samples.

sumably due to fine quartz passing either through or into the body of the rather coarse (5-μm pore size) silver membrane filters where it is screened from the x-rays.

There appears to be a significant difference (15% by peak height and 25% by area) between the calibrations using samples prepared from pure quartz in the laboratory dust chamber and those prepared in Ottawa from a pure quartz using Leroux's technique.[4] Possible reasons for this difference are (1) differences in purity of the prepared samples; (2) differences in size distribution of the samples as suggested by the differences between peak height and peak area; and (3) uneven distribution of dust on the samples collected by the personal sampler, with the central part illuminated by the x-rays having a higher dust density than the edges.

Calibration of Pyrite Samples

Samples of "respirable" pyrite dust on silver membrane filters were prepared by Dr. Machacek using Dr. Leroux's technique of elutriation and filtration. The peak heights and areas were determined with CuKα radiation for the 111 and 200 lines of pyrite; they are shown in Table II together with the signal-to-noise ratio for the strongest line. Some of these results are shown plotted against the mass per unit area in Figure 3. It can be seen that there is a detectable decrease in count per unit mass at higher masses, presumably due to absorption.

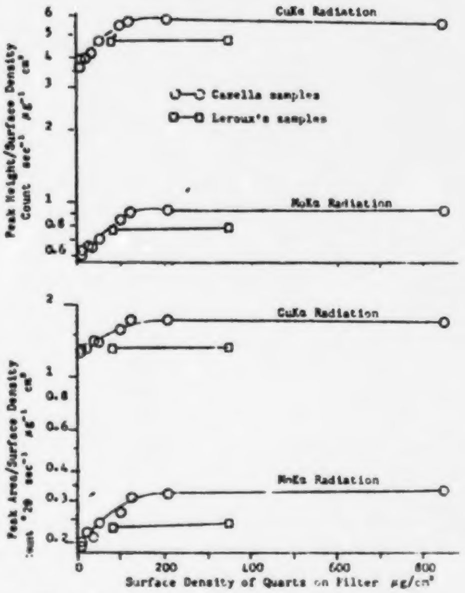

Figure 2. Quartz calibration of x-ray with Casella samples and with Leroux's samples.

Discussion

Choice of Filter

A number of types of filter have been examined in this work, and of those examined that are stable in weight in various relative humidities, the silver membrane, as recommended by Leroux,[2] gives the least background and highest signal-to-noise ratio for the 101 x-ray diffraction line of quartz.

Clearly from the results obtained the choice of membrane filter pore size affects the calibration. For very low masses of dust, the membrane filter having a 5-μm pore size presents only 55 to 60% of the estimated mass of quartz to the x-ray beam. The other 45 to 40% of the quartz either penetrates through the membrane

TABLE II

Calibrations of Pyrite Samples with Copper and Molybdenum Radiation

Mass of Pyrite ($\mu g/cm^2$)	Peak Height (counts sec^{-1})				Peak Area (counts $°2\theta\ sec^{-1}$)				Signal/Noise	
	111 Line		200 Line		111 Line		200 Line		200 Line	
	CuKα	MoKα	CuKα	CoKα	CuKα	MoKα	CuKα	MoKα	CuKα	MoKα
353	210	54	680	175	57.5	12	175	38	17	1.25
333	196	50	644	153	51	11	165	34	17	1.20
249	155	37	520	116	42	8.5	126	26	12	0.85
156	97	24	350	74	24.5	5	86.5	15	10	0.54
156	100	25	364	76	27	5.1	93	16	10	0.52
73	47	11	185	35	12.2	2.5	47	7.4	5.2	0.25

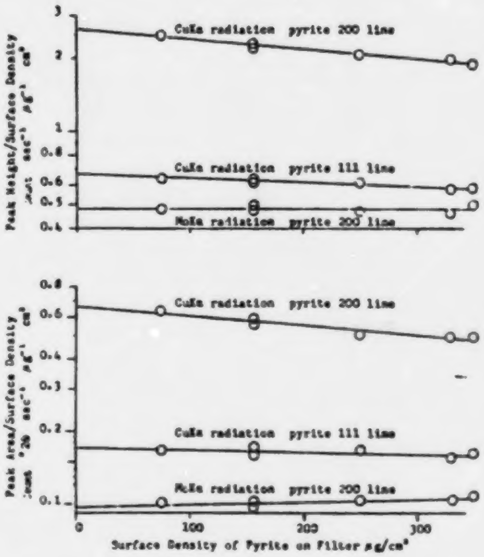

Figure 3. Pyrite calibration of x-ray with Leroux's samples.

or is deposited in the body of the filter where the silver screens it from the x-rays. However, as the dust deposit builds up, the efficiency of presentation of quartz to the x-ray beam increases, reaching 100% when about 40 μg of dust per square centimeter of filter has been collected.

Samples taken on membrane filters having finer pore sizes have yet to be calibrated.

Absorption

It is expected that the most common minerals that will have high absorption for copper Kα radiation will be those containing iron. It can be seen in the log (intensity $\mu g^{-1}\ cm^2$) curves shown in Figure 3 that there is appreciable absorption on pyrite samples, and the x-ray technique using copper radiation would underestimate the quantity of material present by about 25% if the sample contains 150 μg of iron per square centimeter (300 μg of pyrite per square centimeter). This is about the limit of permissible error in quantitative determination of airborne dust; the approximate error can probably be determined by measuring the intensity of a peak (38.0° 2θ) of the silver membrane using copper Kα radiation and comparing with a clean filter (or the back of the test filter).

Resolution

The resolution with CuKα radiation is about twice that obtained with MoKα, and this increase in resolution can be very helpful in separating close lines in mineral mixtures and minimizing interference effects.

Comparison of Copper and Molybdenum Radiations

The advantages of copper radiation are: (1) higher resolution, (2) higher intensity, (3) higher signal-to-noise ratio, and (4) shorter counting time for the same statistical accuracy.

The advantages of molybdenum radiation are lower absorption and longer linear relationships in calibration. However, the higher intensity and signal-to-noise ratio with copper radiation imply that a smaller quantity of material can be detected, and, if the sample area is adjusted for the same statistical accuracy and counting time, the linear limits for both copper and molybdenum Kα radiations are almost the same.

Application to Field Samples

This calibration was applied to samples taken with Casella personal samplers in various hard rock mines and in collieries. With these samples, it is necessary to make some assumption as to the effect of collection of other dust on the efficiency of collection and presentation of quartz. The simple assumption was made that the efficiency is dependent on the total mass of dust collected on the filter in the same way as it is shown to depend on the mass of pure quartz collected. The quantity of quartz was then determined by using the factor given in Figure 2.

On these field samples, peaks were detectable down to peak heights of 20 counts/sec above background, corresponding to 0.02 mg of quartz per sample. By extending the counting time to 100 seconds per step, 0.005 mg was detectable. These masses expressed as concentrations in mine air ranged down to 0.01 mg/m^3 or one-tenth of the threshold limit value, a very satisfactory sensitivity.

Care has to be taken that interference by other minerals is not excessive; for instance, on some samples, muscovite or sericite contributed up to 50% of the intensity of the 101 quartz line. Check analyses were carried out using the next two most intense quartz lines (100 and 112).

Continuing Studies

The continuing work in this program will investigate:

1. The relationship between the peak height, which is easier to measure, and the peak area, which is recommended because it is less sensitive to size distribution changes and to alignment errors.
2. The effect of particle size, using the horizontal elutriator technique[6] for collection of samples.
3. Improvements in sampling and x-ray techniques.
4. Computational techniques – the teleprinter can produce computer-compatible punched tape.
5. Interference by other minerals in quartz determinations and choice of the diffraction line to minimize interference.
6. Extensions to other minerals.

Conclusions

This technique of using personal gravimetric samplers and x-ray diffraction for the determination of respirable quartz dust in mine atmospheres has a sensitivity of about one-tenth of the present threshold limit value.[7]

This technique can be applied without any special preparation of the dust samples after collection.

To avoid fairly large errors it is desirable to calibrate the whole system by taking samples over the whole range of quartz quantities in a pure quartz airborne dust cloud and to check for interference by other minerals, particularly muscovites.

Acknowledgments

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We wish to thank Mr. R. Kowalchuk and the McIntyre Research Foundation for the collection of mine dust samples for examination.

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Section 2—Chapter 15

X-Ray Diffraction Analysis of Quartz in Respirable Dust: Brief Description and Procedure

by

G. Knight

in Proceedings Roundtable Discussion
ANALYTICAL TECHNIQUES for QUARTZ
edited by J.C. Crable pp 30-39a (1972)
American Conference of Governmental Industrial
Hygienists. Cincinnati

Mr. Crable: We are going to return to the discussion of X-ray diffraction. Mr. Geoffrey Knight, who is with the Mining Research Center, Mines Branch, Department of Energy, Mines and Resources at Elliott Lake, Ontario, Canada, is our next speaker. He will be talking to us about X-ray diffraction. Geoff, I think it would be interesting if you would tell us something of the relationship of your department to the government and are you a comparable institution or agency to what Sam Goldberg is doing.

Mr. Knight: We are the Mines Branch in Canada. It has much the same sort of responsibility as the U.S.B.M., but a very much smaller organization. We have only one man working on dust, and one professional on radiation. Some five years ago we were working on the possibility of getting a modern sampling technique for metal mines gravimetric sampling, of course, coming into coal mines looked very promising. We wanted a size selective gravimetric system and an analytical system for quartz. Because it is by far the most dangerous component and is over the whole range of metal mining very variable.

In our first work we did some preliminary experiments on X-ray and infrared, decided that both techniques showed promise of measuring .1 mg. of quartz. The X-ray on silver membrane and the infrared directly on membrane. We selected X-ray ourselves because it seemed much more promising for other minerals which were involved in part of our work, apart from the routine dust sampling. With all the much more information available, it should be easier to rule out interference. I don't know whether we're right or wrong, but at that time we were looking for a sampling method which should carry out 50,000 samples a year of which a large proportion would need X-ray analysis. All those from the higher quartz mines, such as uranium and gold mines in Ontario would need quartz analysis on every sample. We have been working at this over the last five years. We consider we now have a working system using a Casella personal sampler and X-ray analysis with silver membrane filters collecting the dust directly on the filter and with no further handling presenting it to the X-ray unit.

The details are given in this script I've handed out so I'm going to put a bit more emphasis on the other aspects of the program. The present stage in the program is we've completed the laboratory stage of developing the technique of sending technicians out into the mine to do the work. We've been on that for two years. We've taken over 1,000 samples. We're modifying the sampler to increase its convenience in use. We cover the whole range, the sampler and the analytical method. The next stage is the use by the mine staff of this equipment. This will be done in each mine for a few of the mines for a period of six months and in comparison with the techniques of present use. As an aside to our work too, one surface plant crushing silica, we've been using the method for a year now, on an experimental basis. They seem very pleased with it and would like it to be approved by the provincial authorities in our case, so they can put it into routine use.

ANALYSE PAR DIFFRACTOMÉTRIE X DU QUARTZ PRÉSENT DANS DES POUSSIÈRES INHALABLES : BRÈVE DESCRIPTION ET PROCÉDÉS EMPLOYÉS

par

G. Knight*

RÉSUMÉ

Dans ce rapport, on décrit le matériel, les méthodes d'échantillonnage et les techniques d'analyse employés par le Laboratoire d'Elliot Lake, pour doser le quartz dans les poussières aériennes présentes dans les mines. On insiste surtout sur les méthodes employées pour vérifier l'interférence plutôt fréquente et variable que causent les autres constituants des poussières, lors du dosage du quartz.

X-RAY DIFFRACTION ANALYSIS OF QUARTZ IN RESPIRABLE DUST: BRIEF DESCRIPTION AND PROCEDURE

By

G. Knight*

ABSTRACT

This report describes the equipment, sampling method and analytical technique used by the Elliot Lake Laboratory for analysis of quartz in airborne mine dust. Special emphasis is given to the methods used for checking the rather frequent and variable interference found when analyzing for quartz due to other components of the dust.

INTRODUCTION

The object of this program is to develop a technique for airborne dust sampling in mines including quartz analysis with a minimum of handling. It is intended that this will be used in mines on a routine basis, with the X-ray analysis being undertaken at a central laboratory (50,000 samples per year).

Preliminary studies on both X-ray and infrared analytical methods were promising--both X-ray (on silver membrane and vinyl membrane) and infrared (on vinyl membrane) showed a sensitivity, on direct measurement of a 25-mm filter, of less than .05 mg quartz. X-ray was chosen for easier application to other minerals and to sorting out interferences.

BASIS OF TECHNIQUE

1. Copper Kα radiation was chosen because -
   - a) it was more intense than MoKα and higher peak/background ratio;
   - b) it had higher resolution than MoKα (decreases interference); but note -
   - c) graphite monochromator required to avoid Fe fluorescence and resulting lower sensitivity;
   - d) it had lower linear range but linear still to a few times TLV; linearity depends mainly on Fe in sample.

Quartz Analysis: Dust Sampling: Interference

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2. *Equipment:*

Philips (Dutch) stable generator, vertical goniometer, step-scanning scintillation detector, graphite monochromator, automatic sample changer, print-out on paper tape and recorder; 2000-watt Cu tube, 12 x 1.6-mm focus.

3. *Settings:*

Width of beam 12 mm obtained by machining all limiting components; tube 50 kV 40 mA; take-off angle 6°; diverging slit to cover full length of sample at each angle; receiving slit 0.15 mm; step scan 0.04°/step; count between 10 and 40 sec per step; no filter used; recorder 150 mm/hr.

4. *Sample mounting:*

For 25-mm filters, automatic sample-changer holders are drilled 19 mm in diameter on beam centre line and a groove 25 mm in diameter and 0.2 mm deep milled on one face. This groove is lightly covered in petroleum jelly and the filter pressed on with a pipe tool.

5. *Standard samples:*

Standard quartz samples are prepared from a cold-setting resin-quartz mixture in a cell 0.25 mm deep x 22 mm in diameter in the holder of the automatic sample changer; the equivalent mass on the standards is calibrated against pure quartz samples prepared in the laboratory dust chamber; the automatic sample changer holds up to 35 samples; and standards are used in the first and last position.

6. *Results:*

a) peak area was chosen to minimize errors due to distorted filters;
b) calculations are done by a peak search and summation routine on a computer;
c) two standards are checked against each other (indicates constancy of X-ray throughout shift, drifts have occurred);
d) mass on sample determined by comparison of peak area with that of both standards; and
e) correction made for loss of X-ray intensity on light deposits.

7. *Choice of filter:*

a) direct measurement of sample on filter required because most samples in hard-rock mines require quartz analysis;

b) highest density of sample required; therefore, largest pore size (5 μm) at smallest diameter (25 mm) to give full shift collection at 2 ℓ/min;

c) silver membrane chosen for minimum background;

d) but note: 30% loss in X-ray intensity until dust bed builds up--presumably due to masking of quartz by rough silver surface; use of finer filters reduced this problem, but because of lower air flow per unit area at same pressure drop, dust density and sensitivity is reduced;

e) particulates in diesel exhausts can clog filters and full shift samples at more than about 2 mg/m^3 (fine diesel particulates) can be obtained only from larger diameter (32 or 37 mm) filters with corresponding loss of sensitivity; and

f) silver membrane can be ashed with no change in tare (± 0.03 mg) to facilitate determination of ash and combustible dust; quartz can be determined on ashed filters.

g) a range of other types--cellulose acetate, polyvinyl chloride, polyvinyl fluoride, polycarbonate--of dust filters have been examined but none give as low a background as the silver membrane nor are any of them as robust and easy to use. Further advantages of the silver filter are that X-rays are completely absorbed and that there are no spurious diffraction lines from other parts of the apparatus as has been found with semi-transparent filters.

8. Choice of size selective sampler:

The Casella personal sampler was the only one on the market with a 25-mm filter holder; it has the advantage of a dust collection rate about 50% more than that of the 10-mm nylon cyclone instruments and it has proved satisfactory in mine use, but to minimize damage, modifications are required; it is proposed to combine the dust sampler with the cap lamp battery for maximum convenience in mine use and to use a smaller pulsation damper attached to the pump instead of a separate component.

9. Interference:

Interference is the main limitation on quartz analysis and has been found to occur on the three 100, 101, and 112 diffraction lines of quartz that we use, fortunately not all at the same time. Table VII shows the range of intensity ratios for these three lines found in pure quartz and some mine respirable dust samples.

TABLE VII

Ratio of Intensities of Quartz Diffraction Lines

Airborne Dust Samples	Range of Intensity Ratios (integrated peak area)		
	(100)/(101)	(112)/(101)	(112)/(100)
Pure Quartz	0.20 to 0.22	0.083 to 0.10	0.40 to 0.44
Uranium Mines	0.16 to 0.21	0.060 to 0.10	0.40 to 0.45
Gold Mines	0.05 to 0.60	0.150 to 0.18	0.17 to 1.90
Nickel Mine	0.12 to 0.38	0.050 to 0.12	0.23 to 0.50

This shows that in some mines the range in intensity ratios is outside that of pure quartz. This variation is due mainly to interference, and, on most individual samples, there is agreement between two of the lines. It has been found that, for most mines, the 112 line suffers least from interference and that either the 112 or 101 line can be used alone. However, in some mines, the interference varies from one sample to another, presumably depending on mineralogical variations through the mine, and all samples have to be assessed on at least two lines. Our technique is to step-scan each sample and examine resultant background on each side of the quartz peak; if these intensities are anomalous or if the quartz result is high, a check is run on a second diffraction line. The 211 line for quartz is also usable, and when the occasion arises, it will be used to check for interference.

a) Interference by Other Minerals in the Estimation of Quartz

A large number of minerals produce X-ray diffraction (XRD) patterns in which one or more lines are close to the quartz lines. For instance, the common mineral, muscovite, has a strong line at a d-spacing of 3.32Å close to the strongest quartz line at 3.34Å.

Figure 19 shows the two possibilities that can occur with two close lines. In the first, form 1, the two lines merge and appear as a single slightly wider peak and in the second, form 2, the peaks are resolved but when integrating the area using the normal assumption of a linear background correction the hatched area would be omitted.

A number of approaches to this problem are possible, the following have been examined:

1. *Identification of minerals present in the ore from mine geologists' data and choosing a quartz line that is clear of interference.*
2. *XRD scanning of ore and airborne-dust samples from the mine and identifying minerals present and again choosing a quartz line that is clear of interference.*
3. *Visual checking of the XRD scan of each sample for adjacent peaks and departure from normal shape.*
4. *Examination of the ratios of intensity of the various quartz diffraction lines and eliminating the lines which give rise to ratios markedly different to pure quartz samples.*
5. *Comparing the estimates of quartz on each sample when using a number of diffraction lines.*
6. *Computer analysis of each scan using curve fitting with least squares criterion.*

The first approach entailed obtaining mineralogical reports from the mine geologist. However, these reports were not adequate to determine the XRD patterns using standard references for many minerals, particularly those with variable composition such as the pagioclases, and it was necessary to confirm the patterns using appraoch 2. In this a number of samples of ore and host rock were obtained from the mine, crushed and scanned by XRD. This approach was successful in some cases where the number of minerals present in significant quantity is small, for instance the Elliot Lake uranium mines where the only interference found is muscovite (sericite) on the (101) quartz line. But for mines with a large number of minerals present in significant quantity, such as the Timmins Gold mines, the analysis could not be completed. In this case, even after confirmation and identification of seven minerals in the XRD pattern, some strong lines were not allocated to minerals.

The third approach is useful in detecting form 2 errors and samples which become misplaced in the automatic sample changer. But otherwise in only one case has useful information been gained from the shape of the diffraction line. When form 2 errors are seen it is expected that this line will lead to a low estimate of the quartz content and so the result should be discounted.

In the fourth approach the ratio of intensities of three quartz diffraction lines are compared. The range of results obtained from four types of dust samples are shown in Table VII.

Table VII shows that only in the case of the uranium mines is it possible to conclude that there is no significant interference on two of the lines and some on one of them, the (101). For the other mines the range of ratios on all three comparisons is such that no conclusions can be drawn.

In the fifth approach three estimates of the quartz on each sample is made using the three strongest diffraction lines of quartz that are clear of the diffraction pattern of the filter material (silver metal). The results obtained from a representative range of samples is shown in Table VII. It can be seen that there is reasonable agreement between the three estimated in many cases but in others the differences are up to a factor of 3 to 1. Form 2 errors were found on some samples on the (100) line. It is assumed that as form 1 errors are not observable and give rise to high estimates of quartz, the best estimate of the quartz content is given by the lowest-observed estimate that does not show form 2 errors.

The sixth approach, form fitting with least squares criterion using a computer, has been used successfully for separation of overlapping lines in many similar problems, for instance in gas chromatography. However, in our case with diffraction lines that are weak with respect to background the preliminary examination suggested that long counting times and extended scanning widths would be necessary for a successful analysis. This approach does not seem as promising as producing multiple estimates of quartz from various diffraction lines and has not been investigated further.

Discussion of Interference

It is clear that interference is a serious problem in quartz analysis and that considerable effort could be spent in checking for interference on each sample. To minimize effort it is necessary to consider the object of dust sampling and quartz analysis in mines. The requirement in most sampling is to demonstrate that the dust levels are below some legally defined limit or threshold level at which a hazard to health arises. In this case all samples indicating quartz dust levels less than this and free of form 2 errors (visual inspection of chart recorder) can be reported as having a maximum (rather than an estimated) quartz content. Samples with form 2 errors and quartz contents above the threshold limit need to be analyzed on a second quartz line to determine the maximum quartz content or confirm the high estimate. It may even be required to extend this analysis to a third line for some mines.

In the mine samples analyzed to date it appears that the (112) quartz line is the least subject to interference and is most suitable for the first estimate. However, the (101) line has eight times the intensity and a slightly greater sensitivity

ERRATA

Page 36 - The table referred to as Table VII on page 36 was omitted in the text. It is given below.

Comparison of Estimates of Quartz Derived from Three Diffraction Lines

Sample	Estimate of Quartz ($\mu g/cm^2$) from Respective Line		
	(100)	(101)	(112)
Gold Mine	8	8	8.3
	7.5	10	19
	1.6	.6	.66
	121	66	70
	3.5	8.1	4.4
	1.1 [1]	3.4	3.0
	2.1	1.3	2.8
	33.5	17	15
	1.8 [1]	6.9	8.8
Nickel Mine	3.6	7	6.6
	10	14	14
	18	21	14
	11	20	19
	24	24	22
	24	23	26
	6 [1]	18	17
	21 [1]	44	37

[1] adjacent peak seen on recorder trace, discard as low estimate is expected from the form 2 interference

Page 37 - First line - Replace 'For instance,' by ', as, for instance, '.
- Third line - Replace ', the' by '. The'.

and is more suitable in some mines. For instance, in the Elliot Lake uranium mines where muscovite gives only a small and reasonably consistent contribution to the quartz peak, the (100) line is least sensitive because of the higher background at the lower angle and to date has appeared to be the least useful of the three lines examined.

10. Sensitivity:

a) the 101 line is the most intense and has the highest sensitivity whereas the 112 line, though only 15% as intense, has almost the same sensitivity because of the lower background and lower intensity of interference at the higher angle; the 100 line is the least sensitive because it has the highest background and most interference;
b) with pure quartz samples it is possible to detect peaks down to 1 μg in the beam but in an unknown sample, one can only be sure that the peak examined is due to quartz rather than interference at more than 5 μg in the beam.

11. Accuracy:

a) repeatability of calibration: individual readings have a standard deviation of 4%, much greater than the deviation due to counting statistics--0.5%--following Klug and Alexander; two factors enter into this: 1) variations in step position relative to peak and 2) Klug and Alexander's formula assumes well-defined shoulders for integration of peak area; in practice, statistical variations in shoulder position give rise to significant uncertainties in calculated peak areas; on most mine samples, we probably achieve repeatability of 10% or 5 μg whichever is the greatest; in relationship to the TLV of 0.1 mg/m^3, this is similar to gravimetric relative to a TLV of 2 mg/m^3.

12. Calibration of X-ray analysis:

a) Evenness of deposition on filter: all sampling systems give an uneven deposit to some extent depending on size distribution; on some cassettes, an appreciable proportion is collected on the internal surfaces rather than on the filter; calibrations of the types of dust samplers that we possess give up to a 30% range in X-ray intensity/mass ratio on one filter size; for different filter sizes the X-ray intensity/calculated mass in beam (assuming even deposition) varies over a range of 40%.

b) the effect of pore size is important on light dust samples; we assume that the efficiency of quartz presentation to the X-ray beam is dependent on the total mass of dust on the filter rather than on the mass of quartz; and

c) we feel that the whole system of sampling and X-ray analysis requires calibration to give reasonable accuracy on small samples and that calibration using quartz specimens prepared by wet filtration or other techniques may lead to considerable errors of the system; however, we use such techniques for other minerals.

13. Time:

one run through automatic sampler per shift (33 samples); considerable time could be saved by the use of an on-line computer.

14. Training:

little is needed for running X-ray analysis of quartz; interpretation of interference and checking for errors requires experience.

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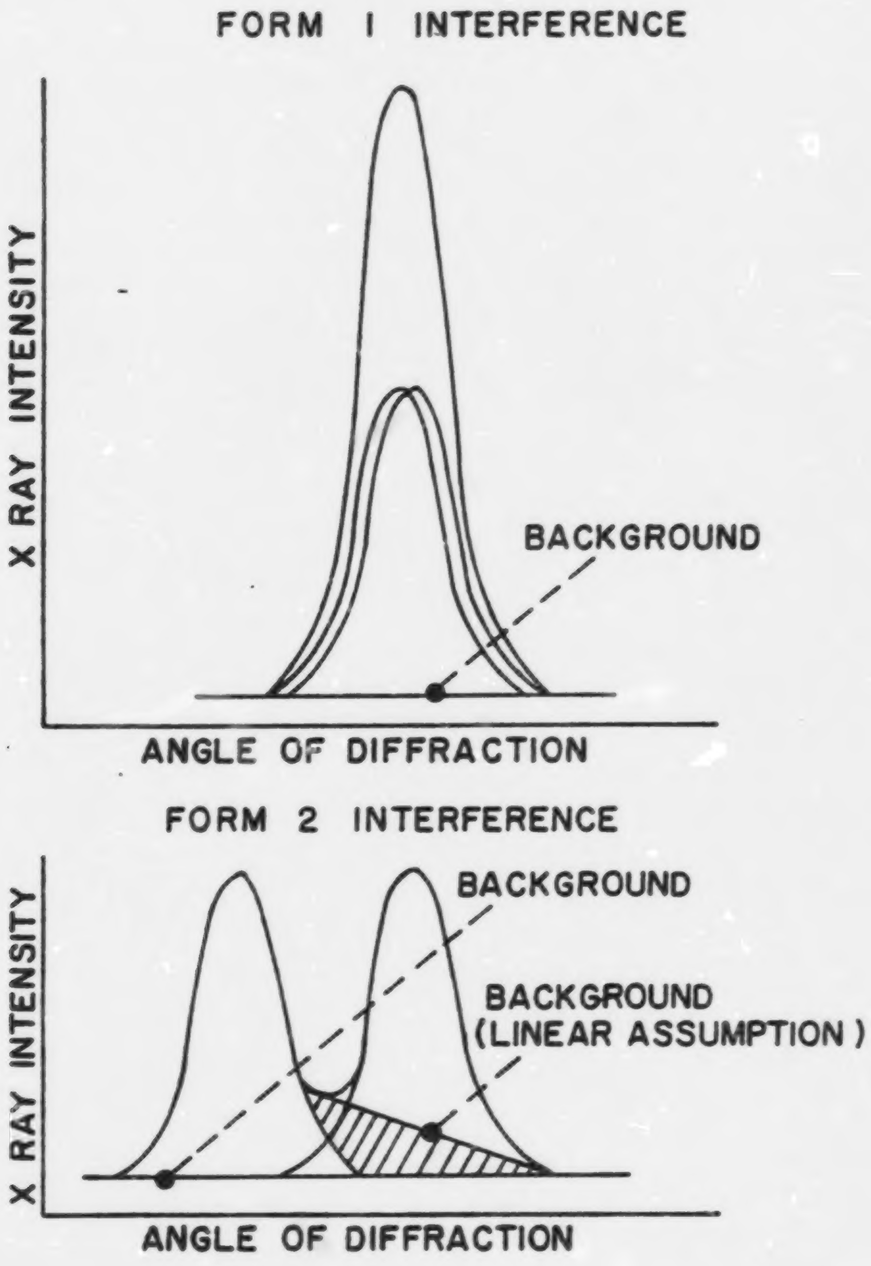
FORM 1 INTERFERENCE
X RAY INTENSITY
BACKGROUND
ANGLE OF DIFFRACTION
FORM 2 INTERFERENCE
X RAY INTENSITY
BACKGROUND
BACKGROUND
(LINEAR ASSUMPTION)
ANGLE OF DIFFRACTION

Figure 19. (Knight) Forms of interference in X-ray diffraction patterns

2. 16

Section 2—Chapter 16

Overlap Problems in Counting Fibers

by

G. Knight

American Industrial Hygiene Association Journal
36 (2) pp113-114 (1975)

Problèmes du recouvrement des fibres lors du dénombrement de celles-ci

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On a calculé la probabilité que surviennent certaines erreurs de dénombrement des fibres, causées par un recouvrement accidentel de ces fibres durant l'étape d'échantillonnage, et l'on a démontré que ces probabilités étaient significatives. On justifie l'établissement de règles simples qui permettront aux microscopistes d'obtenir des valeurs de numération concordantes.

Overlap Problems in Counting Fibers

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The probabilities of certain errors in counting fibres due to accidental overlaying during sampling are calculated and shown to be significant. Justification is given for simple rules to get agreement in counting between microscopists.

CLEARLY, WHEN PARTICLES OR FIBERS are collected on a surface, some may be accidentally deposited on top of others.[1,2] It is usual to count crossing fibers, *i.e.*, all four ends clearly resolved, as two. However, if two fibers meet, *i.e.*, only three ends resolved, microscopists differs in their approach and some count them as two fibers and some as one bundle. Therefore it is desirable to lay down some simple rules to standardize fiber counting.

In this note, the probability of fibers crossing and meeting by accidental overlay during sampling is considered.

Armitage[2] has considered overlap problems for rectangular laminae of length *kl* and the breadth *l*, he gives:

$$N/C = 1 + (4N/\pi A)\,[\{(1 + k)^2 + \pi k\}\,\nu^2 + \pi k\,\nu_2]$$

in which N is the number of particles originally present in the air and C is the number of clumps, A is the area of deposit, whilst ν is the mean and ν_2 the variance of the distribution of l.

The treatment is symmetrical about length and breadth and, for fibers, it is more convenient to consider l as the length and kl as the thickness. Then, by the usual definition of fibers, k is always less than 0.33. For the long fibers, which contribute mainly to the value of ν, k tends to zero. Therefore, taking k to zero, one can obtain the approximate expression:

$$N/C = 1 + (4N/\pi A)\nu^2$$

For the 5% permissibe counting error, the counting limit N_L is given by

$$(4N_L/\pi A)\nu^2 = 0.05$$

The area of a filter of 37 mm diameter is 10 cm/² (10⁹ μm²), and, if the mean fiber length, ν, is assumed to be 50 μm, N_L = 15,000 fibers which, at a threshold limit value (TLV) of 5 fibers/cm³ corresponds to a sample volume only only 3 liters and overlap errors would be large on the normal sample of 10 to 20 litres. However, this includes both crossing and meeting errors.

The position for calculating accidental meeting errors is shown in Figure 1. Here, t is fiber thickness and R is projection needed for resolution of fiber end. Clearly a meeting error will occur if either end of the second fiber falls within the area of the rectangle, defined by $t^1 + R$, in which R is the resolution of the microscope, and $l + 2R + t_2/2 \sin\theta$. Therefore, following Armitage's treatment and neglecting $t_2/2 \sin\theta$ and R relative to l, we can obtain the approximate expression,

$$N/C = 1 + 2.\,(4N/\pi A)\,(\sigma + R)\nu$$

where σ is the mean thickness of the fibers. Again for a 5% error,

$$2.\,(4N_L/\pi A)\,(\sigma + R) = 0.05$$

and inserting the value of ν previously used and assuming values of 1 μm for the resolu-

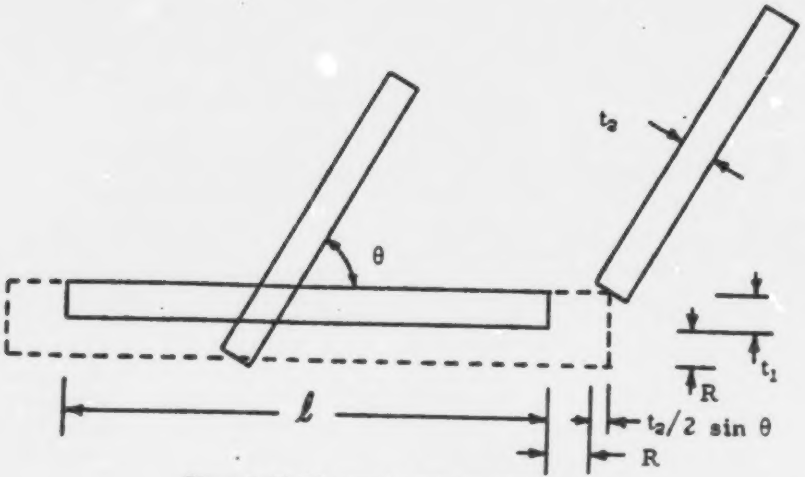

Figure 1. Limiting positions for meeting fibers.

tion R and 3 μm for the mean fiber thickness, σ, gives $N_L = 100{,}000$ fibers which corresponds to a sample volume of 20 liters at the TLV, *i.e.*, about that usually used.

Thus accidental meeting errors can be significant if the product of mean fiber length and mean diameter is as great as 150 μm^2. However, in most samples of asbestos, it is less than this and the simple rule of counting a pair of fibers as a fiber bundle (one count), if all four ends cannot be resolved, will give rise to an insignificant error and minimize differences between microscopists.

Acknowledgment

This note was prepared for the ACGIH-AIHA committee on Aerosol Hazard Evaluation and the author thanks its members for their helpful comments and criticisms.

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Section 2—Chapter 17

The Use of an On-line Computer to Control Quantitative XRD Analysis

by

G. Knight

in Proceedings of the Fourth Symposium on Electron Microscopy and X-Ray Application to Environmental and Occupational Analysis, 1980.
edited by P.A. Russell pp171-185 Butterworths 1984

CHAPITRE 14

Emploi d'un ordinateur en ligne pour maîtriser l'analyse quantitative par diffractométrie X

G. Knight

Cette étude fait partie du programme de recherches entrepris par le ministère de l'Énergie, des Mines et des Ressources sur l'environnement des mines souterraines, 4.3.0.2.01.02. Le Laboratoire d'Elliot Lake a mis au point un système d'échantillonnage des poussières qui permet d'obtenir des évaluations gravimétriques et de diffractométrie X, pour le dosage des poussières inhalables et de leur fraction composée de quartz [Knight, 1978]. L'échantillonneur de poussières contient un classificateur à impact, de deux pages, et recueille la portion inhalable des poussières aériennes sur une membrane d'argent de 25 mm de diamètre avec calibre des pores de 5 µm qui peut être directement insérée, après pesée, dans le diffractomètre X.

On a employé un programme informatique pour calculer l'aire située sous la crête. On l'a mis au point à partir d'un programme publié prévu pour la spectrométrie gamma [Kemper et Van Kempen, 1970]. Knight a décrit son élaboration sous forme de programme autonome pour l'analyse par diffractométrie X avec largeur et temps de numération fixes. Durant les années d'exploitation de ce programme, il s'est avéré que l'on pouvait considérablement accroître la capacité de traitement des échantillons analysés par diffractométrie X de la façon suivante :

1. en effectuant une numération des échantillons lourds de quartz pendant seulement une brève période, à chaque étape;
2. en effectuant une numération des échantillons légers de quartz, lorsque la largeur des crêtes est plus petite;
3. en transférant rapidement les données, et en éliminant le temps requis par une imprimante mécanique;
4. en effectant une analyse multiligne d'un échantillon en une passe à travers l'échangeur automatique d'échantillons.

La figure 1 montre des échantillons typiques, lourds et légers, et leur corrélation avec le bruit de fond typique observé.

Le programme informatique en ligne était, au moment de la rédaction de cet article, exploité depuis quelques mois, et comme l'on pourrait s'y attendre, comporte encore quelques défauts. On présente ce programme en annexe, et toute personne intéressée à adapter ce programme à un système informatique précis d'analyse par diffractométrie X peut se procurer une version à jour, disponible sur bande perforée.

CHAPTER 14

The Use of an On-Line Computer to Control Quantitative X-Ray Diffraction Analysis

G. Knight

This study forms part of the Energy, Mines and Resources research program on underground mine environment, 4.3.0.2.01.02. The Elliot Lake Laboratory has developed a dust sampling system for use with gravimetric and XRD assessments for respirable dust and its quartz portion [Knight 1978]. The dust sampler has a two-page impaction size selector and collects the respirable portion of the airborne dust on a 25 mm diameter, 5 μm pore size, silver membrane filter ready for direct insertion, after weighing, into the X-ray diffractometer.

A computer program has been used for the calculation of the area under the peak. This was developed from a published program intended for gamma spectrometry [Kemper and Van Kempen 1970]. Its development as an off-line program for use on XRD analysis using fixed width and counting time was described by Knight. During the years that it was in use, it was clear that considerable gains in XRD sample throughputs could be obtained by:

1. counting heavy quartz samples for only a short period of time on each step;
2. counting light quartz samples for a narrower peak width;
3. rapid transfer of data and elimination of the time taken by a mechanical printer;
4. multi-line analysis of a sample on one pass through the automatic sample changer.

Figure 1 shows typical heavy and light samples and their relationship to the typical background noise found.

The on-line computer program has, at the time of writing, been in use for a few months and, as can be expected, still has a few bugs in it. The program is given in the appendix and an up-to-date version can be made available on paper tape to anyone interested in adapting it to a specific computer XRD system.

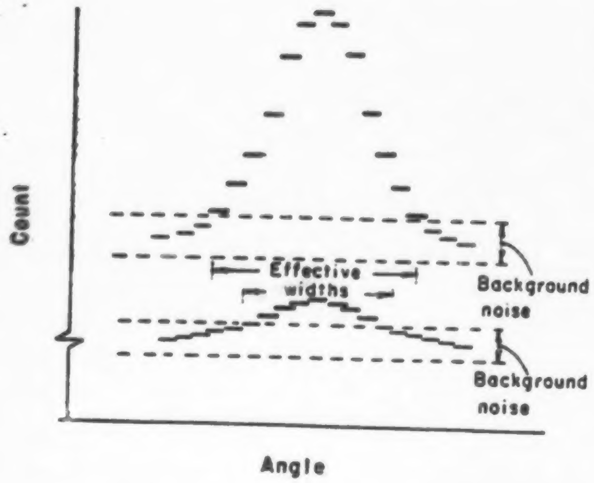

Figure 1. Comparison of smoothed strong and weak peaks showing statistical background fluctuations.

DESCRIPTION OF THE SYSTEM

The X-ray diffractometer is a Philips unit with vertical goniometer, cobalt high-intensity tube, graphite monochromator, scintillation detector, and automatic sample changer of 1970 vintage. The Philips equipment has been updated by increasing the beam width to 12 mm from the original 10 and by installing a stepping motor and motor controller, PW1935. The computer is a DEC PDP8 equipped with two tape files, teletype, programmable clock, 36 digital input-output channels (3 units) and eight A/D input channels. The two units are connected through an interface that changes the logic, produces pulses and operates relays as required to suit the various pieces of equipment connected.

The interface enables the computer to put out co m ands and receive data as listed in Table I. The number of channels used is also shown. m

DESCRIPTION OF THE PROGRAMS

The computer programs are written in Fortran II and a symbolic assembly language SABR. SABR can be mixed in with Fortran and used to define and carry out operations not available in Fortran, such as controlling the clock, digital input-output and A/D input.

The program consists of four parts:

1.	the line search and count subroutine	GKXRSR
2.	the sample control, calculation and output main program	GKXRMN

Table I. Interface

	Command	*Input*	*No. of Channels*
Motor controller			
1	Set goniometer angle		17
2	Slew command		1
3		Slew complete	1
Counter			
4	Reset		1
5	Start		1
6	Stop		1
7		Count	24
Sample changer			
8	Start		1
9	Change sample		1
10	Bypass sample		1
11	Reset		1
12		Sample number	A/D
13		Sample in position	1
Generator (designed but not installed)			
14	Start		1
15	Reduce tube settings		1
16		Tube current	A/D
17		Tube voltage	A/D

3. the data file GKXRIN
4. the data file preparation program GKXRPD

The first part, subroutine GKXRSR, first scans the region in which the peak is expected using a short counting time and compares the highest value with the mean of the seven counts. If it is not significantly greater [less than P*SQRT (Count)] it recounts for up to a set limit (total counting time of 12, 37 or 110 seconds per step) (Figure 2).

If no significant peak is found, control is returned to the main program with a zero mass for quartz.

If a significant peak is found, a check is made to see if the peak lies outside the possible region of the quartz diffraction line. If so, INTERFERENCE is identified and a RETURN to GKXRMN occurs (Figure 3). This region is wide enough to allow for the peak displacement that can occur with distorted filters.

delete

Having found a significant peak in the quartz region, the region on either side is scanned to identify the shoulders; these are defined by counts that are not significantly lower than the previous two counts (Figure 4). At this stage the background slope is measured and all further tests of significance are made after correcting the

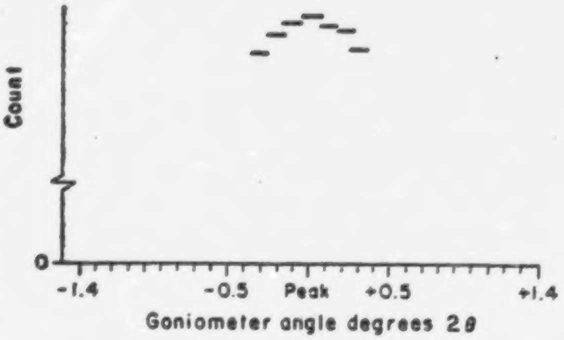

Figure 2. Peak hunt—recount at longer time (if maximum count is not significantly greater than mean count).

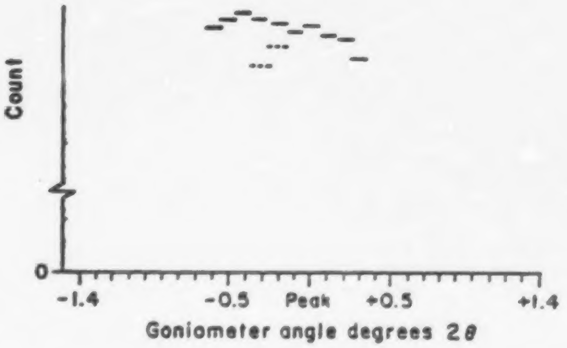

Figure 3. Complete peak region (if new maximum count is outside peak region, consider it an interference).

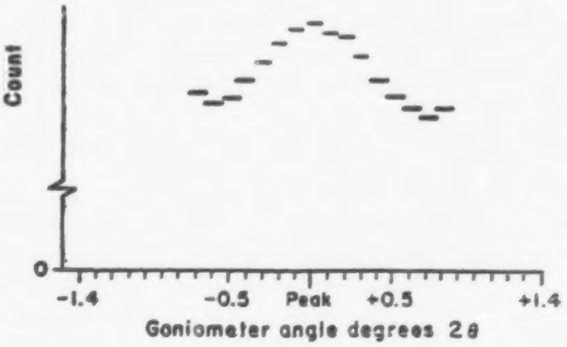

Figure 4. Finding shoulders—(count −2) (not significantly greater than count).

counts for this measured slope, which vary substantially from sample to sample (Figure 5). It should be noted that the counts have already been corrected for the slope found on clean filters or very light samples because it maximizes the efficiency in detecting or rejecting peaks with very low dust weights.

The next step is to count the background (Figure 6). The region counted starts at each shoulder and is half the width of the peak on each side. During this process checks are made for adjacent peaks, defined as two successive counts significantly greater than the mean. If these two counts are found the background counting is stopped. Close peaks occur frequently and can raise the indicated background significantly, particularly on light samples if the fixed background width required for heavy samples is used.

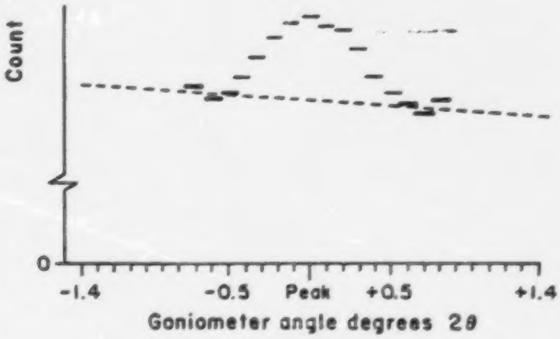

Figure 5. Calculate background slope (from mean of each set of three counts).

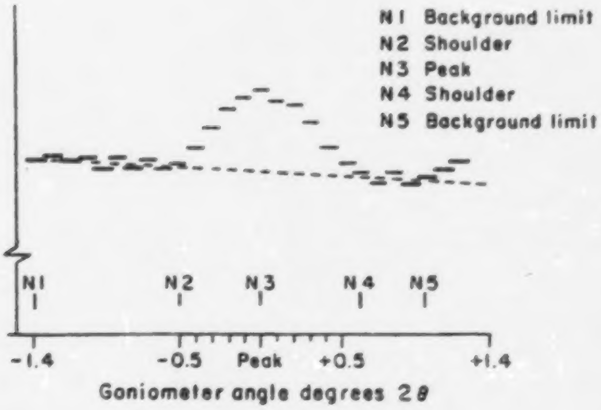

Figure 6. Finish counting background and refine shoulder (shows line profile as developed by computer program with on right a near peak and the point at which this stopped counting).

The final step is to refine the position of the two shoulders.

This subroutine also contains the goniometer angle, slew and counter control subroutines written largely in the symbolic assembly language SABR.

The main program, GKXRMN, controls the automatic sample changer, calculates the area under the peak, using the information returned from GKXRSR, and writes out the results.

Manual input from the teletype tells the computer how many samples are to be run, and how many and which lines are to be analyzed. Up to four quartz lines with Miller indices of 1, 0, 0; 1, 0, 1; 1, 1, 2 and 2, 1, 1, as well as four nonquartz lines, can be examined. Manual input from the switch register is also used and controls facilities that can be changed during processing:

1. finish analysis and start new batch
2. suppress printout detailing results of each line (useful in debugging and identifying analytical problems)
3. stop further quartz analysis on one sample when two lines are in agreement
4. set probability level used for tests of peak significance (high values increase counting time and accuracy)
5. set longest count rate used (the longer times are useful only for higher accuracy estimates of samples with little quartz)

There is a facility for either doing all quartz lines or stopping as soon as two quartz lines are in agreement. On the standard, necessarily the first sample in the sample changer, all four quartz lines are run and compared with the results obtained previously and stored in GKXRIN data file. This comparison is useful to check that XRD is correctly set up, and is given in Table II together with the results of an

Table II. Loading program and results (underlining relates to added comments)

```
R LOADER
*+UFA1 :GKXMN2.RL,DTA1:GKXSR2.RL/I/O/R/G
# SAMP = 32  # LINES = 4 ORDER LINES = 1234          Manual entry
AMEND 1,CONT RT
DATA S# L# STTUS COUNTS
S# TM SLPS BUS NTHT AREA
  0 1 0 29046. 28972. 29134. 28568. 29395. 29795. 29162. 30092. 30384.
 31431. 34148. 38269. 44829. 50045. 51189. 42203. 31304. 29059. 28414.
 28269. 27877. 27476. 27731. 27712. 27310. 27269. 26927. 27012. 25736.
511 10  1  6 15 25 29 23  5  -9.06  -8.16  2705.  2897.  2318. 10632.

STANDARD AREA LAST RUN   2376.1  0
  0 2 0 20817. 20472. 21025. 21037. 20963. 21497. 22239. 23946. 27771.
 36416. 55135. 89903.116780.142268.139518. 70839. 27813. 22101. 20932.
 20325. 19980. 19518. 19381. 19211. 19297. 19002. 19032. 19844. 19351.
511 10  1  2 14 22 29 25  3 -12.56  -6.99  1917.  2084. 12232. 52976.
STANDARD AREA LAST RUN  12774.8  0
  0 3 0     0.     0.     0.     0. 13297. 13032. 12423. 12544. 13234.
 13966. 17815. 21958. 27971. 34794. 30123. 21406. 14572. 12898. 12747.
 12763. 12045. 12161. 12242. 12080. 12649. 12771.     0.     0.     0.
511 10  7  8 14 21 24 23  6  -4.49  -3.01  1213.  1258.  2248.  8553.
STANDARD AREA LAST RUN   1935.9  0
  0 4 0 10935. 11037. 10881. 10928. 10899. 10996. 11046. 11145. 11374.
 12005. 13387. 16536. 20979. 26399. 23042. 18758. 14144. 11776. 11197.
 11220. 11184. 10961. 10869. 10893. 11219. 10816. 10946. 10794.     0.
511 10  1  8 14 22 27 21  4   2.15  -0.28  1092.  1097.  1546.  5998.
```

Table II. Loading program and results (underlining relates to added comments) *(continued)*

```
STANDARD AREA LAST RUN   1434.6  0
TABLE S#5 STATUS & PK POSITIONS / MASSES
qtz line 1,0,0  1,0,1  1,1,2  2,1,1    E5     E6     E7     E8
  1511   117    118    117    117      0      0      0      0
          4.335  2.996  2.983  4.383  0.000  0.000  0.000  0.000  sample number
  2511   115    115    115    116      0      0      0      0
          1.734  1.606  1.792  1.744  0.000  0.000  0.000  0.000  A/D sample number
  3511   115    115    115    115      0      0      0      0
          1.678  1.622  1.608  1.824  0.000  0.000  0.000  0.000  STATUS
  4511   115    115    115    115      0      0      0      0       0 = no sig. peak
          1.823  1.593  1.465  1.847  0.000  0.000  0.000  0.000  1 = normal
  5511   115    115    115    115      0      0      0      0       2 = interference
          1.798  1.570  1.481  1.751  0.000  0.000  0.000  0.000  4 = slew failure
  6511   116    115    115    116      0      0      0      0       5 = counter
          0.972  0.916  0.857  0.876  0.000  0.000  0.000  0.000      failure
  7511   116    115    115    115      0      0      0      0
          0.747  0.677  0.596  0.690  0.000  0.000  0.000  0.000  position of peak
  8511   114    115    115    115      0      0      0      0       15 = centre
          0.213  0.239  0.207  0.204  0.000  0.000  0.000  0.000  quartz mass
  9511   513    513    115    115      0      0      0      0
         -5.102 -4.274  0.272  0.264  0.000  0.000  0.000  0.000
 10511   115    115    115    115      0      0      0      0
          0.733  0.635  0.592  0.674  0.000  0.000  0.000  0.000
 11511   115    115    115    115      0      0      0      0
          0.717  0.657  0.617  0.625  0.000  0.000  0.000  0.000
 12511   115    115    115    115      0      0      0      0
          0.732  0.679  0.606  0.748  0.000  0.000  0.000  0.000
 13511   115    115    115    115      0      0      0      0
          0.663  0.646  0.565  0.706  0.000  0.000  0.000  0.000
 14511   115    115    115    115      0      0      0      0
          0.501  0.467  0.498  0.516  0.000  0.000  0.000  0.000
 15511   115    114    115    115      0      0      0      0
          0.432  0.449  0.411  0.473  0.000  0.000  0.000  0.000
 16511   515    515    513    513      0      0      0      0       status 2,4,5
         -5.102 -4.274 -5.214 -6.208  0.000  0.000  0.000  0.000  result in large
 17511   513    513    513    514      0      0      0      0       negative mass
         -5.102 -4.274 -5.214 -6.208  0.000  0.000  0.000  0.000
 18511   113    114    114    114      0      0      0      0
          0.210  0.206  0.164  0.220  0.000  0.000  0.000  0.000
 19511   115    114    115    114      0      0      0      0
          0.254  0.208  0.167  0.202  0.000  0.000  0.000  0.000
 20511   115    115    115    115      0      0      0      0
          0.211  0.223  0.193  0.257  0.000  0.000  0.000  0.000
 21511   115    115    115    115      0      0      0      0
          0.267  0.237  0.208  0.298  0.000  0.000  0.000  0.000
 22511   114    114    114    114      0      0      0      0
          0.255  0.228  0.225  0.253  0.000  0.000  0.000  0.000
 23511   115    115    115    115      0      0      0      0
          0.226  0.248  0.226  0.275  0.000  0.000  0.000  0.000
 24511   113    113    113    114      0      0      0      0
          0.048  0.080  0.078  0.084  0.000  0.000  0.000  0.000
 25511   115    115    115    115      0      0      0      0
          0.062  0.093  0.084  0.119  0.000  0.000  0.000  0.000
 26511   116    115    115    115      0      0      0      0
          0.043  0.067  0.064  0.077  0.000  0.000  0.000  0.000
 27511   116    115    115    115      0      0      0      0
          0.030  0.051  0.038  0.046  0.000  0.000  0.000  0.000
 28511   114    114    114    114      0      0      0      0
          0.024  0.048  0.029  0.049  0.000  0.000  0.000  0.000
 29511   116    115    116    115      0      0      0      0
          0.047  0.049  0.052  0.074  0.000  0.000  0.000  0.000
 30511   115    115    116    115      0      0      0      0
          0.008  0.022  0.022  0.013  0.000  0.000  0.000  0.000
 31511   114    114    114    114      0      0      0      0
          0.005  0.016  0.022  0.013  0.000  0.000  0.000  0.000
 32511   210    220    115    112      0      0      0      0
         -5.102 -4.274  0.000  0.005  0.000  0.000  0.000  0.000
# SAMP
```

analysis showing the status (0 indicates nonsignificant peak; 1 normal; 2 interference; 4 and 5 control failures), the peak position and the mass of quartz or other component.

The data file GKXRIN was introduced to enable the standard to be compared with previous results as a check on performance and XRD settings. It is also used for entering a data list used in the programs such as background slopes, peak angles, counting times and the control variables for the interface between the computer and the XRD.

The program GKXRPD was written for loading data into the data file GKXRIN.

The program and subroutine when loaded with system and library functions occupies about 10,000 twelve bit memory spaces in the computer. The main program GKXRMN is close to the limit of the symbol table, limiting the format statements and the explanations of the outputs and inputs.

RESULTS AND CONCLUSIONS

This program had, at the time of writing, been used successfully for about 1000 samples. During this period a certain amount of refining, particularly input and output, has continued. Crosschecks between this technique and the previous off-line technique have shown agreement within the statistical accuracy expected.

Further refinement will no doubt be introduced as familiarity with the system increases, with the objective of decreasing time of analysis or improving readability of output.

Possibly the output will be linked to the dust record files and analysis required for daily, monthly and longer period reports that are desirable.

REFERENCES

Kemper, A. and Van Kempen, G.A. (1970) "A simple computer program for high resolution gamma ray spectroscopy," *J. Radional Chem.* 6:461-475.

Knight, G. (1978) "Mine dust sampling system-CAMPEDS," *CANMET Report* 78-7; Energy, Mines and Resources Canada.

Appendix

Computer Programs

The computer programs are written in Fortran II language with, when required, symbolic assembly language (SABR) statements. These SABR statements have an S in the first column and are separated by semicolons. Comments are given following a C in the first column or following S..../. The S....\KI construction indicates that the variable KI is a Fortran variable used in SABR. The semicolon separates machine instructions on a line. The SABR language is essential for machine language instructions when they are not defined in Fortran as in the digital input-output, analog to digital input and clock instructions. This language is also easier to use than Fortran for subroutine control and some computations.

```
        SUBROUTINE CKXPSR
C       NAME CKXPSR.FT SUBROUTINE FOR COMPUTER CONTROL OF XRAY DIFFRACTION
        COMMON C,UANG,B,IP,KI,[illegible]
        DIMENSION C(29),KT(4),NS(7),AC(4)                          / Definitions
S       OPDEF DRI0 6504!OPDEF DRI1 6514!OPDEF DRI2 6524   / digital input
S       OPDEF DR20 6505!OPDEF DR21 6515!OPDEF DR22 6525   / digital output 4K
S       OPDEF DR00 6506!OPDEF DR01 6516!OPDEF DR02 6526   / digital output 0V
S       OPDEF CLZE 6130!OPDEF CLDE 6132!OPDEF CLSA 6135!OPDEF CLSK 6131 / clock
        P=1.5
S       CLA CLL!OSR!AND P1!SNA!JMP PA1!CLA CLL/  PROBABILITY FROM SR
        P=P+1.4
S       PA1, CLA CLL!OSR!AND P2!SNA!JMP PA3!CLA CLL
        P=P+2.
S       PA3, CLA CLL!OSR!AND P4!DCA \K1  /READ SR FOR LONGEST CNT TIME
        DO 100 N=1,29
100     C(N)=0
        I2=0
C       COUNTS PEAK OVER 4 TIMES
        B1=8
        Y=0
        X=0
        N1=21
        DO 101 I=1,K1
        KU=KT(I)
        I2=I2+KU
        UK=KU
C       FINDS PEAK
        DO 102 N=12,18
S       JMS ASCT
201     C(N)=C(N)+W
        Y=Y+W
        IF(C(N)-X)102,102,103
103     X=C(N)
10      FORMAT(14I5)
        N1=N
        NS(3)=N
102     CONTINUE
C       SIGNIFICANCE OF PEAKS
        W=Y/7.
        X1=SQRT(W)
        W=X-W
        IF(W-P*X1)101,105,105
101     CONTINUE
105     KU=I2
        UK=KU
        IF(W-X1)107,107,106  / checks trace quantities
107     IR=-1                / -1 = status "no significant peak"
        RETURN
C       FINISH COUNTING PEAK REGION
106     N2=N1-3
        N3=N1+3
        X=0
        DO 108 N=N2,N3
        IF(C(N))109,109,139  /
109     CONTINUE             / counts step if not previously
S       JMS ASCT             /    counted, i.e., C = 0
202     C(N)=W
139     IF(C(N)-X)108,108,127
127     X=C(N)
        N1=N
        NS(3)=N
108     CONTINUE
        N=IABS(15-N1)
        IF(N-4)129,128,128
128     IR=1                 / 1 = status "interference"
        RETURN
129     CONTINUE
C       DO RIGHT AND THEN LEFT SIDE OF PEAKS
C       FIND SHOULDER
        DO 114 I=1,2
        I2=3-I-I
        N=N1+I2+I2+I2
        J2=IABS(15+10*I2-N1)
        DO 111 J=1,J2
        N=N+I2
        IF (C(N)) 112,112,113
112     CONTINUE
S       JMS ASCT
203     C(N)=W
113     W=C(N)
        W=W+SQRT(W)
        IF(W-C(N-I2-I2))111,114,114
111     CONTINUE
C       FIND BACKGROUND
114     NS(5+I)=N
        N2=NS(6)
        N3=NS(7)
        X=N2+N2+N2-N3-N3-N3-6
        B=(C(N2)-C(N3)+C(N2-1)-C(N3+1)+C(N2-2)-C(N3+2))/X
        DO 110 I=1,2
        I2=3-I-I
        X=I2
        Y=0
        J2=(N2-N3)/2
        N=NS(5+I)-I2
        DO 119 J=1,J2
        N=N+I2
        IF(N-29)115,116,123
115     IF(N)123,123,116
116     IF(C(N))120,120,121
120     CONTINUE
S       JMS ASCT
204     C(N)=W
121     X1=J
        Y=Y+C(N-I2-I2)-X1*X*B
        W=Y/X1
        W=W+1.5*SQRT(W)
        J1=0
        IF(C(N)-W-(X1+2.)*X*B)119,119,122
122     J1=-1
        IF(C(N-I2)-W-(X1+1.)*X*B)119,123,123
119     CONTINUE
123     N=N+J1*I2
        Y=0
C       REFINE SHOULDER
        NS(3+I2+I2)=N-I2
        J2=IABS(N-N1)-3
        IF(J2)135,135,136
135     J2=1
136     DO 124 J=1,J2
        X1=J
        N=N-I2
        Y=Y+C(N)+X1*X*B
        W=Y/X1
        W=W+1.5*SQRT(W)
        IF(C(N-I2)-W+(X1+1.)*X*B)124,124,125
125     IF(C(N-I2-I2)-W+(X1+2.)*X*B)124,124,126
124     CONTINUE
126     NS(3+I2)=N
110     CONTINUE
11      FORMAT(7F10.3)
        W=B/UK+B1
        IH=0        / 0 = status "normal"
        RETURN
S       P1, 0010;P2, 0020;P3, 0040;P4, 0007
S       ASCT,   0000   /ANGLE SET & COUNT SUBROUTINE
C       UANG IS PEAK ANGLE AND A(7) IS STEP SIZE
        DO 132 L=1,5
        X1=N-15
        Y1=UANG+AC(8)*X1
        I4=Y1/100.
        X1=I4
        Y1=Y1-100.*X1
        LA=10.*Y1
        X2=LA
        K1=100.*Y1-10.*X2+16.*X1
S       JMS INVER
        I5=K0
```

```
C      UA..G=AMC.DE; I4=A ; LA=CH ; [illegible]
       I3=LA/100
       I4=LA/10
       I3=100*I3
       I4=LA-10*I4
S      STA;CLZE;[illegible]   /CLEARS CLOCK ANGLE SLEW
S      CLA CLL;TAD    \KE;CLDS  /SETS CLOCK
S      CLA CLL;TAD \KI;TAD \KI;IAC \KF;[illegible];CLA CLL /[illegible] SET SIM
S      JMS CLA;JMS CLA;CLA CLL;TAD \I1;TAD \I3;DCA \KI
S      JMS INVER
S       CLA CLL;TAD \KO;DRZ0  /SETS ANGLE
S      CLA CLL;TAD \I5;TAD \L;DRZ1   /SETS ANGLE AS SET SLEW
S      CLA CLL;TAD \KE;DRZ2  ;CLA CLL  /RESETS COUNTER
       DO 133 K=1,50
S      JMS CLA;CLA CLL;DRI2;AND \LF;SNA;JMP AA;CLA CLL  /CHECKS SLEW DONE
133    IR=3      / 3 = status "slew problem"
       GO TO 132
S      AB, CLA CLL;TAD \KG;DRZ2;CLA CLL  /STARTS COUNTING
       DO 130 K=1,KU
S      JMS CLA
S      CLA CLL
130    CONTINUE
S      CLA CLL;TAD \KF;DRZ2   /STOPS COUNTING
S      CLA CLL;DRI0;DCA \KI   /READS 3 DECADES OF COUNT
S      JMS INVER
       X1=KK
S      CLA CLL;DRI1;DCA \KI   /READS NEXT 3 DECADES
S      JMS INVER
       Y1=KK
       N=1000.*Y1+X1
       IF(N)132,134,131
134    IR=4          / 4 = status "counter problem"
132    CONTINUE
        RETURN
131    X1=N-15
       [illegible]=-X1*B1*UK
S      JMP I ASCT
S      CLW, 0000    /CLOCK WAIT SUBROUTINE   / 0.4096 sec
S      CLSA;A4, CLSK;JMP A4;JMP I CLW        / time delay
S      INVER,0000 /SR INVERTS DIGIT ORDER IN KI TO KO
S      CLA STL RAR;DCA K4;DCA \KO;DCA \KK  /& CONVERTS INVERSE BCD
S      IAC;AA,  DCA K2                     /INTO BINARY
S      TAD \KI;AND K4;SNA ;JMP AB   /INPUT DIGIT
S      CLA CLL;TAD K2;TAD \KO;DCA \KO  /OUTPUT DIGIT
S      IAC;DCA K6;TAD K2;AND K5;SZA;JMP AC  /1ST DECADE
S      TAD K7;DCA K6;TAD K2;RTR;RTR;AND K5;SZA;JMP AC /2ND DECADE
S      TAD K8;DCA K6;TAD K2;RTR;RTR;RTR;RTR   /3RD DECADE
S      AC,    CIA;DCA K3;AD,    TAD K6  /MULTIPLY DECADES BY BCD INPUT
S      ISZ K3;JMP AD;TAD  \KK;DCA \KK /BCD OUTPUT IN BINARY
S      AB,    CLL CLA;TAD K4;RAR;DCA K4  /NEXT INPUT DIGIT
S      CLA CLL;TAD K2;RAL;SZA;JMP AA  /NEXT OUTPUT DIGIT
S      CLA CLL
S      JMP I INVER
S      K2, 0000;K3, 0000;K4, 0000;K5, 0017;K6, 0000;K7, 0012;K8, 0144
       STOP
       END
$
```

Subroutine INVER required mostly because interface wired with 12 leads in inverse order. The B.C.D. to binary could be carried out more simply in Fortran.

```
C       NAME GKXRMN.FT COMPUTER CONTROL OF XRAY DIFFRACTION
C       FORTRAN AND SABR LANGUAGES
        COMMON C,UANG,B,I,KT,KU,UK,NS,AC
        DIMENSION A(8),AC(8),OS(8,34),NR(8,34),LO(8)
        DIMENSION C(29),KT(12),NS(7),ANG(8),LS(8),PK(8),OM(8)
S       OPDEF  DRI2 6524
S       OPDEF  DRZ2 6525
S       OPDEF  DRO2 6526
S       OPDEF  CLZE 6130
S       OPDEF  CLDE 6132
S       OPDEF  CLSA 6135
S       OPDEF  ADLM 6531
S       OPDEF ADST 6532
S       OPDEF  ADCL 6530
S       OPDEF  ADRB 6533
S       SKPDF CLSK 6131
S       SKPDF  ADSK 6534
        CALL IOPEN('DTA1','GKXRIN')
        READ(4,10)A,AC,BK,OM,ANG,KT,KB,KC,KE,MF,MG,KF,KG,KH,LO
101     WRITE(1,11)
        READ(1,13)M1,L1,LS
        WRITE(1,24)
        READ(1,13)I
        IF(I)101,102,101
102     WRITE(1,14)
        DO 105 I=1,272
        NR(I)=0
105     OS(I)=0
        DO 100 N=0,M1
S       CLA CLL;TAD \KB;TAD \KC;DRZ2;CLA CLL;TAD \MG;DRO2 /CL ASC CNTRLS
S       STA;CLZE;CLA CLL;TAD \KE;CLDE;JMS CLW  /SET CLOCK
S       CLA CLL;TAD \MG;DRZ2;JMS CLW;JMS CLW;CLA CLL;TAD \MG;DRO2 /NXTSA
S       CLL/CLA
        DO 145 J=1,100
S       JMS CLW;CLA CLL
145     CONTINUE
S       A3, DRI2;AND \MF;SZA;JMP A3;CLA CLL  /READ DSC BUSY
S       ADCL;ADLM;ADST;A4, ADSK;JMP A4;ADRB;DCA \MS  / A/D S#
        X=MS
        MS=X*AC(1)-AC(2)
        IF(N) 104,103,104
103     DO 132 L2=1,4                             /
        UANG=ANG(L2)                              /
S       JMS CNTCAL                                / standard
        WRITE(1,23)N,L2,C                         / for
        WRITE(1,19)MS,KU,NS,B,B1,X,Y,X1,W         / comparison
        WRITE(1,17)A(L2),I                        / in
132     A(L2)=W                                   / position # 1
        DO 140 L=5,8                              / in sample
        L2=LO(L)                                  / changer
140     A(L)=A(L2)                                /
        GO TO 100                                 /
104     LS=1
        DO 106 L=1,L1
        L2=LS(L)
        IF(L2-5)137,136,136
137     IF(LS)106,106,136
136     UANG=ANG(L2)+AC(3)
S       JMS CNTCAL
S       CLA CLL;OSW;AND T4;SZA;JMP A6;CLA CLL  /WRITE LINE RESULTS
        WRITE(1,23)N,L2,C
        WRITE(1,19)MS,KU,NS,B,B1,X,Y,X1,W
S       A6, CLA CLL
        W=W/A(L2)*OM(L2)
        NR(L2,N)=100*I+N3+100
        OS(L2,N)=W
        IF(L2-5) 108,106,106                      / compares r
108     GO TO (106,116,114,106)L                  / with
114     L3=LS(2)                                  / previous
        Y=OS(L3,N)                                / results
        IF(1.12*W-Y+.02)115,118,115               / if equal
115     IF(.88*W-Y-.02)118,118,116                / read
116     L3=LS(1)                                  / switch register
        Y=OS(L3,N)                                / and if set
        IF(1.12*W-Y+.02)105,118,117               / rejects analysis
117     IF(.88*W-Y-.02)118,118,106                / of further
118     CONTINUE                                  / quartz lines
```

```
S      CLA CLL;OSR;AND T5;SZA CLA /IF = 90 WIPE LINES
106    CONTINUE
S      CLA CLL;OSR;AND T2;SNA;JMP A3;SNA;JMP TA1;CLA CLL;JMS TABLE
S      TA1, CLA CLL;OSR;AND T3;SNA;JMP TA2;CLA CLL /AT INTRVALS
       IF(M-10)100,134,135
135    IF(M-20)100,134,100
134    CONTINUE
S      JMS TABLE;TA2, CLA CLL
100    CONTINUE
       M=M-1
S      A5, CLA CLL
S      JMP TABLE
       CALL OPEN('DTA1','CKAMIN')
       WRITE(4,10)A,AC,BK,ON,ANC,KT,KB,KC,KE,NF,NG,KF,KG,KH,LO
       CALL OCLOSE
       GO TO 101
S      T2, 6000;T3, 1000;T4, 0400;T5, 0200;T6, 0100
S      CNTCAL, 0000 /COUNT CALCULATE SUB ROUTINE
       B=BK(L2)
       CALL CKXRSW
       N3=NS(3)
       IF(I)130,107,138
130    W=0
S     JMP I CNTCAL
138    W=-A(L2)
S      JMP I CNTCAL
C      CALCULATE PEAK AREA
107    X=0
       Y=0
       W=0
       N1=NS(1)
       N2=NS(2)
       N4=NS(4)
       N5=NS(5)
       DO 109 N=N4,N5
109    X=X+C(N)
       DO 110 N=N1,N2
110    Y=Y+C(N)
       DO 111 N=N2,N4
111    W=W+C(N)
       X1=N5-N4+1
       X=X/X1/UK
       X1=N2-N1+1
       Y=Y/X1/UK
       X1=N4-N1
       X2=N5-N2
       X3=N4-N2+1
       X4=N5+N4-N2-N1
       W=W/UK-(X*X1+Y*X2)*X3/X4
       B1=(X-Y)/X4*2.
       X1=N5-N3
       X2=N3-N1
       X3=N5-N1
       X1=C(N3)/UK-(X*X1+Y*X2)/X3
S      JMP I CNTCAL
S      CLK, 0000;CLSA;A2, CLSK;JMP A2;JMP I CLK /CLOCK WAIT SR
S      TABLE, 0000   /SUB GIVES OUTPUT TABLE
       WRITE(1,25)
       DO 150 J=1,N
150    WRITE(1,22)J,NR(1,J),NR(2,J),NR(3,J),NR(4,J),NR(5,J),NR(6,J),
      CNR(7,J),NR(8,J),OS(1,J),OS(2,J),OS(3,J),OS(4,J),OS(5,J),OS(6,J),
      COS(7,J),OS(8,J)
S      JMP I TABLE
10     FORMAT(40A6,20A2)
11     FORMAT('IN #S I # BORDER LNS-I3')
13     FORMAT(20I3)
14     FORMAT('DATA S L CNTS'/'S IN POS# SLPES BGS HTHT AREA')
17     FORMAT('STAND AREA LAST A STATUS',F9.1,I3)
19     FORMAT(9I3,2F7.2,4F7.0)
22     FORMAT(I5,8I7/10X,8F7.3)
24     FORMAT('AMEND 1,CONT RT')
25     FORMAT('RSLTS S# STTS APK POS/MASS')
23     FORMAT(/I3,I4,9F7.0,2(/10F7.3),/)
       STOP
       END
```

```
C       NAME GKXRPD.FT
C       PREPARE DATA FOR GKXRIN DATAFILE USED IN MAIN PROGRAM GKXRUN
        DIMENSION A(8),AC(8),BK(8),OM(8),ANG(8),KT(4),KC(8),JC(8),LO(8)
        WRITE(1,21)
        READ(1,22)J
        IF(J)29,29,30
29      CONTINUE
        CALL OOPEN('DTA1','GKXRIN')
        READ(4,10)A,AC,BK,OM,ANG,KT,KC,JC,LO
        WRITE(1,9)A
        WRITE(1,11)BK
        WRITE(1,12)OM
        WRITE(1,13)ANG
        WRITE(1,14)AC
        WRITE(1,15)KT
        WRITE(1,16)KC
        WRITE(1,17)JC
        WRITE(1,18)LO
30      WRITE(1,20)
        READ(1,22)I
        GOTO(31,32,33,34,35,36,37,38,39)I
31      WRITE(1,11)BK
        READ(1,23)BK
        GO TO 30
32      WRITE(1,12)OM
        READ(1,23)OM
        GO TO 30
33      WRITE(1,13)ANG
        READ(1,23)ANG
        GO TO 30
34      WRITE(1,14)AC
        READ(1,23)AC
        GO TO 30
35      WRITE(1,15)KT
        READ (1,22)KT
        GOTO 30
36      WRITE(1,16)KC
        READ(1,22)KC
        GO TO 30
37      WRITE(1,17)JC
        READ(1,22)JC
        GO TO 30
38      WRITE(1,18)LO
        READ (1,22)LO
        GO TO 30
39      CALL OOPEN('DTA1','GKXRIN')
        WRITE(4,10)A,AC,BK,OM,ANG,KT,KC,JC,LO
        CALL OCLOSE
9       FORMAT('AREAS UNDER STANDARD PEAKS'/8F9.0)
11      FORMAT('#1 BACKGROUND SLOPES FOR 8 LINES'/8F7.3)
12      FORMAT('#2 QUARTZ MASSES FOR 8 LINES'/8F7.3)
13      FORMAT('#3 PEAK ANGLES IN DEG 2THETA FOR 8 LINES'/8F7.3)
14      FORMAT('#4 REAL CONSTANTS:8F7.3'/8F7.3)
15      FORMAT('#5 COUNTING TIMES IN 0.4 SEC UNITS'/4I5)
17      FORMAT('#7 INTEGER CONSTANTS MAIN'/10I5)
18      FORMAT('#8 AREA OF WHICH QTZ LINE TO BE USED FOR LINES
       C 5-8 CALC'/8I5)
20      FORMAT('ENTER 1 TO 8 FOR CORRECTIONS TO ABOVE #S ; 9 TO STOP')
21      FORMAT('FOR NEW GKXRIN FILE ENTER 1 ;FOR OLD PRESS RETURN')
22      FORMAT(10I5)
23      FORMAT(8F7.3)
        STOP
        END
```

NOTE ADDED IN PROOF

Over 10,000 samples have now been run. The major developments are counting times have been limited to two steps; 4 & 16 secs. for the stronger lines and 8 and 32 secs. for the weaker lines. A high precision option with longer times is available.

Calibration Constants can be stored for 15 types of dust sampler differing in dust deposition pattern.

Light Sample Correction Factors for three pore sizes of silver membrane filters are selectable.

Absorbtion - A correction subroutine has been developed based on the intensity of the silver peaks through the dust layer.

Diagnostics - Print-out options have been improved for examining machine functions and interference.

Section 2—Chapter 18

Interlaboratory Crosscheck of Quartz Analysis on Mine Airborne Dust Samples

by

G. Knight

American Industrial Hygiene Association Journal
45(9) pp655-660 (1984)

Contre-vérification entre laboratoires des analyses du quartz faites sur des échantillons de poussières aériennes recueillies dans des mines

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Dans ce rapport, on décrit les résultats d'une comparaison des analyses du quartz faites par 9 laboratoires, dont 4 utilisent la technique canadienne de dépôt direct sur filtre, et 5 la technique américaine de transfert sur un second filtre. Six laboratoires ont employé la méthode de diffractométrie X, et 3 la spectrométrie d'absorption infrarouge. Dans une usine de concentration du minerai de fer, on a recueilli les échantillons en appliquant à la fois les systèmes canadien et américain d'échantillonnage. En général, les résultats obtenus par les laboratoires concordaient avec une marge de ± 20 %, quant au dosage du quartz déposé sur les filtres. Les résultats de certaines analyses se sont avérés être des points aberrants. On a noté une tendance à une plus forte proportion d'aberrations et à des aberrations plus importantes dans les valeurs obtenues par les laboratoires utilisant une technique de transfert. Cependant, il est possible que la raison en soit les dommages subis par les échantillons lourds durant leur expédition. Il est évident que l'on doit faire d'autres comparaisons pour déterminer les avantages des diverses méthodes.

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Interlaboratory Crosscheck of Quartz Analysis on Mine Airborne Dust Samples

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This report describes the results of a comparison of quartz analysis between 9 laboratories, 4 of which use the Canadian direct-on-filter technique, and 5 the American transfer-to-second-filter technique. Six laboratories used X-ray diffraction, and 3 infra-red absorption. The samples were collected in an iron ore concentrating mill using both Canadian and U.S. sampling systems. The laboratories mostly agreed within ±20% of each other in determining the proportion of quartz on the filters. Some analyses appeared to be outliers. There was a tendency for a higher proportion of, and larger, outliers among the laboratories using a transfer technique. However, it may have been due to damage to the rather heavy samples during shipping. It is clear that further comparisons are required to determine the merits of the various methods.

Introduction

During the course of the Labrador West mixed dust pneumoconiosis study over 10 000 airborne dust samples were collected for both occupational and environmental purposes during the one year study period.(1) Some 8000 of these samples were analyzed by the Elliot Lake Laboratory for quartz. The Elliot Lake Laboratory uses a direct-on-filter X-ray diffraction technique under computer control.(2,3)

During the course of this study it became apparent that there was substantial interference on about one quarter of the samples, which might possibly be avoided by use of the transfer technique used in many of the North American laboratories followed by X-ray diffraction or infra-red absorption assessment of quartz.(4,5)

Thus it was decided that a crosscheck should be carried out with a number of laboratories using the U.S. developed technique which had also been used by the mining companies in previous years. A second major difference between the Canadian and U.S. quartz sampling and analysis systems is the respirable dust sampler used. The Canadian system developed for mines, in its first stage, used a metal cyclone calibrated against the British Medical Research Council's respirable dust specification, while the American system uses a plastic (nylon) cyclone calibrated against the American Conference of Governmental Industrial Hygienists specification.(2,6,7) Thus, to prepare samples for an interlaboratory crosscheck it is also desirable to use both sampling techniques.

Experimental Design

The design included multiple side by side sampling at two sites, 1214140 and 1224166. These sites were representative of the major areas giving interference problems and where the dust concentrations were high enough to collect a few milligrams of dust in an eight-hour sampling period.

The design laid out for each site is shown in Table I. This was carried out by the technician with two errors. First, Gelman DM filters were used instead of the type of PVC usually used in the U.S.A., and secondly the type IV 37 mm diameter filters were all cut to 25 mm after sampling as had

TABLE I
Experimental Design

Filter No.	Sample Type Code No.	Sample Type Orig. H&H	Filter Diam. mm	Filter Type	Flow Rate L/min	Laboratory
1	I	H&H[A]	25	Ag	1.9	A,B,C,A
2	"	"	"	"	"	"
3	"	"	"	"	"	"
4	"	"	"	"	"	"
5	"	"	"	"	"	"
6	"	"	"	"	"	"
7	"	"	"	"	"	"
8	II	"[B]	25	DM	"	A,D,A,
9	"	"	"	"	"	A,D,A,
10	III	Nylon[C]	37	Ag	1.7	A,B,C,A
11					"	A,B,C,A
12	IV	Nylon[D]	37	PVC	"	A,(E,A)[E,F]
13					"	A,(E,A)
14					"	A,(G,A)
15					"	A,(H,A)
16					"	A,(I,A)
17					"	A,(H,A)
			Error Correction Design			
18	I	H&H[G]	25	Ag	1.9	A
19		"		"	1.9	A
20	IV	Nylon[H]	37	DM	1.7	E,A
21	IV	"		"	"	A,F,A
22		"		"	"	A,G,A
23		"		"	"	A,H,A
24		"		"	"	A,I,A
25		"		"	"	A,H,A

[A] Standard sampler used in Labrador study.

[B] Same as[A] Modified for direct-on-filter IR.

[C] Nylon sampler as tested using direct-on-filter XRD — center 25 mm cut out for analysis.

[D] A common U.S. sampling system.

[E] Laboratories E to I have been requested to return transferred samples to Elliot Lake if suitable for XRD analysis.

[F] Filters cut to 25 mm and thus bracketed part not carried out.

[G] Repeat test using duplicate type I.

[H] Same as IV, but not cut and shipped to Laboratories E to I.

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been the usual practice for shipping to Elliot Lake for analysis. The error in the filter type was not noticed in time to correct, however the laboratories using the dust transfer technique accepted this type of filter. The second error was overcome by resampling both sites with type IV samplers and duplicate type I to compare the two sampling days.

The nine selected laboratories are designated by the letters A to I and the filters sent to each are shown in Tables 2 and 3. Laboratories A to D are Canadian laboratories who normally analyze direct-on-filter samples. Laboratories E to I all normally use transfer techniques and are all accredited under the AIHA laboratory accreditation program and take part in the NIOSH P.A.T. program for silica. Two of these laboratories use IR and three XRD.

Results

The detailed dust and quartz weights obtained by each laboratory are not included but are available from the author. The calculated quartz percentages are given in Tables II and III.

It is apparent that there were some dust losses on the silver membrane samples from site 1224166 in circulating through the laboratories and returning to Laboratory A. These were heavier than normal, about 4 mg, and such a high proportion of visibly damaged deposits has only been noticed on much heavier samples when received from the field at Laboratory A. All the 25 mm diameter silver membrane filters were reweighed after the final quartz analysis. The filters, with the exception of those from day I site 1224166, indicated a decrease in gross weight of 0.1 to 0.23 mg. While this averages 8% of the dust weight, it is also about the difference found when comparing the tare weights of filters on two balances in different laboratories, as is the case here. Also, one laboratory necessarily touches an unanalyzed portion of the filter during mounting, thus the small losses can be apportioned between weighing errors and handling effects. However, the six filters from day I site 1224166 which were analyzed show weight losses of 0.40 to 2.23 mg, corresponding to 10 to 50% of the dust on the filters. The seventh filter, BH19, showed a weight loss of 3.5 mg (75%).

TABLE II
Results Expressed in % Quartz: Site 1214140

Type No.	Filter No.	A[A] 1,0,1[B]	A 2,1,1	A 1,1,2	A 1,0,0	A Match[C]	B 1,0,1	C 1,0,1	Others[A] XRD	Others[A] IR
I	BH1	25	32	21	41	23	27	32		
	2	24	31	19	35	32	26	18[D]		
	3	24	35	22	31	28	28	32		
	4	25	35	21	40	30	28	33		
	5	24	30	21	34	23	27	25		
	6	24	35	21	36	29	29	33		
	7	25	32	21	34	33	28	31		
	Mean	25	33	21	36	29	27	31		
II	DM21					-				[A]D26
	22	32	40	26	51	-				D25
III	CH1	20	22	16	12	21	22	28		
	2	22	20	11	30	22	23	21		
IV	D801	28	31	18	38	32				
	802	26	31	16	27	28				
	803	28	18	16	30	29				
	804	26	39	15	49	-				
	805	27	31	20	28	28				
	806	29	35	15	17	(33)				
	Mean	27	31	17	32	27				
I	BH24	30	39	27		28				
	25	28	38	23	33	(36)				
IV	D825								E23	
	826									F22
	827								G29	
	828								H30.5	
	829									I28
	830								H27.2	

[A] Letters refer to laboratory code.

[B] Miller indices for quartz lines. The differences in results indicate interference.

[C] Match found between one pair of values. ( ) means match outside normal tolerance.

[D] Excluded because of reported damage.

TABLE III
Results Expressed in % Quartz: Site 1224166

Type No.	Filter No.	A[A] 1,0,1[B]	A 2,1,1	A 1,1,2	A 1,0,0	A Match[C]	B 1,0,1	C 1,0,1	Others[A] XRD	IR
I	BH15	21	33	21	33	21	19	16		
	16	20	32	19	37	20	20	19		
	17	21	30	20	31	21	23	22		
	18	25	35	23	33	24	26	24		
	19	20	29	18	27	19	15	-		
	20	24	34	22	41	23	24	26		
	21	23	30	22	41	22	23	23		
	Mean	22	31	21	35	22	21	22		
II	DM25	20	26	15	36					[A]D30
	26	12	85	18	12					D28
III	CH5	22	26	16	46	24	22	20		
	6	21	20	15	34	26	23	24		
IV	D813	25	32			(32)[C]				
	814	25	33			(33)				
	815	24	29							
	816	23	28							
	817	23	32							
	818	25	31							
	Mean	24	31							
I	BH22	20	33	22		21				
	23	20	36	23		21				
IV	D819								E14	
	820									F10
	821	30							G28	
	822								H22.4	
	823									I25
	824	31							H21.1	

[A] Letters refer to laboratory code.

[B] Miller indices for quartz lines. The differences in results indicate interference.

[C] Match found between one pair of values. ( ) means match outside normal tolerance.

[D] Excluded because of reported damage.

The quartz analysis indicated that losses of 7 to 34% on these six filters had occurred. This did not correspond to the weight losses which resulted from damage near the edge of the filter in handling. Evidently the results from these filters are unreliable, but even so Laboratory A found good agreement of the quartz percentages obtained between most filters on day 1 and day 2. Although one filter, BH25, is high at 36%, this is within the limits of error on weighing.

Discussion

It is apparent that there are large differences between the side by side samples taken on day 1 at site 1224166. The spread of weights, not reported here, for one instrument type is larger than the ±10% ±0.1 mg usually found. This is probably due to real differences in dust concentration induced by fluctuating winds and poorly mixed dust airstreams. It has been observed in mills near open windows that there is a visible boundary between 'clean' and 'dusty' air and that this boundary is very mobile. Unfortunately, this renders the analysis of the results less accurate as the determined quartz weights cannot be compared directly, but must be compared through the derived quartz percentages which necessarily also include weight assessment errors.

There are differences between the relative weights of dust collected by the different types of instruments on different days. This is presumably also due to real differences in dust concentration between the groups of samplers, although they were close together. The comparisons of sampler types has been studied specifically using a more suitable experimental layout and is reported elsewhere.[8]

The mean and range of quartz percentage reported by each laboratory are given in Figure 1 and in rank order in Table IV.

It can be seen that the first two (results 10 and 14%) laboratories from site 1224166 are clearly outliers. The last two laboratories (results 28 and 29%) from 1224166 and the first two (results 22 and 23%) from 1214140 are possible outliers.

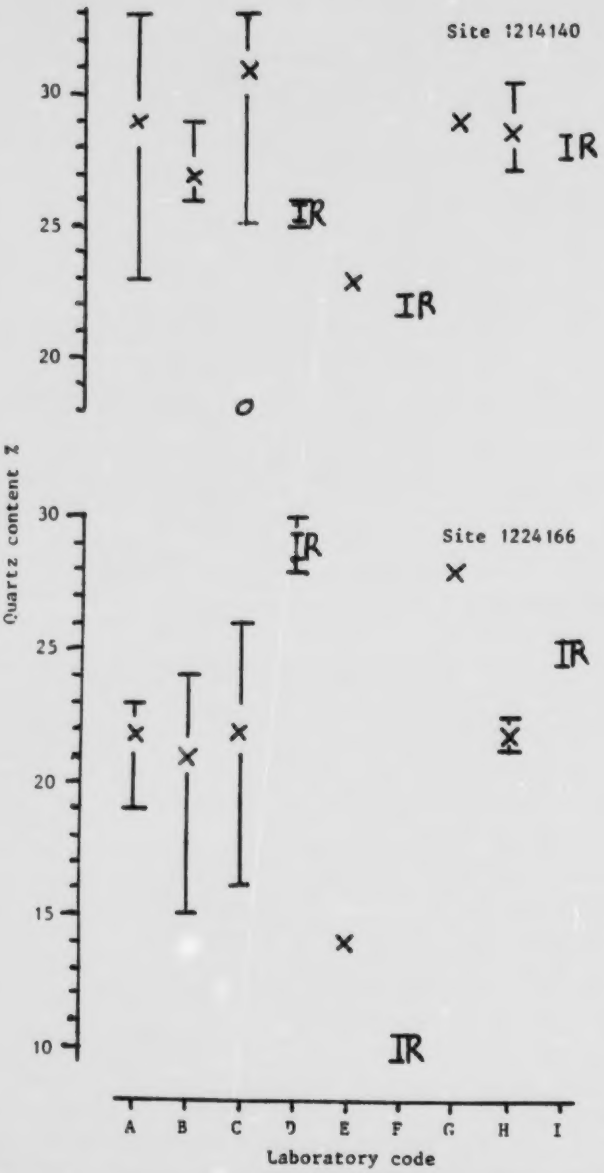

Figure 1 — Means and range for laboratories using XRD (X) and Infrared (IR).

The results do not suggest that there is a significant difference between IR and XRD, and the cause for the clear outliers 10 and 14% appears to be loss of dust during transport or transfer. The 14% result was confirmed by Laboratory A when repeating the analysis on the redeposited dust on the returned silver membrane filters.

Interference with these particular samples was reported by Laboratories A (XRD), B (XRD) and D (IR). These laboratories all use a direct-on-filter technique and do some checks for interference. It is not clear whether the other laboratories, including all those with transfer techniques, did not check for interference or whether their treatment removed the interfering minerals.

TABLE IV
Ranking of Quartz Analysis Results by Laboratory at Each Site

		Site						
	Lab	1214140			Lab	1224166		
Lowest %	F	22	(1)[A]	IR[B]	F	10	(1)	IR
	E	23	(1)	XRD[C]	E	14	(1)	XRD
	D	25.5	(2)	IR	B	21	(7)	XRD
	B	27	(7)	XRD	H	21.7	(2)	XRD
	I	28	(1)	IR	C	22	(6)	XRD
	M	28.8	(2)	XRD	A	22	(7)	XRD
	A	29	(7)	XRD	I	25	(1)	IR
	G	29	(1)	XRD	G	28	(1)	XRD
Highest %	C	31	(7)	XRD	D	29	(2)	IR

[A] The number in brackets is the number of filters analyzed by each laboratory.

[B] Infra red absorption.

[C] X-ray diffraction.

The major objective of this study was to compare the Canadian direct-on-filter method with the U.S.A. transfer to second filter method. This is shown in Table V using mean and standard deviations from one analysis on each filter.

It can be seen that the two methods are within one standard deviation of each other at each site. The omission of two outliers from each set only makes a significant effect on the transfer technique results at one site.

The main features of the techniques used by the various laboratories are outlined in Table VI. This table covers the major factors involved. These factors are discussed below.

Direct-on-Filter (DOF) Versus Transfer

The DOF technique has the advantage of substantially less handling which is reflected in the cost difference between A and laboratories E to I. However, this is not the only factor in Laboratory A's cost as it is set up to analyze 10 000 samples per year in batches of 34. DOF requires calibration using samples collected with the specific sampler in an airborne pure quartz dust cloud. The transfer technique has the advantage that it isolates the sampling from the analytical procedures and some laboratories use chemical treatment

TABLE V
Comparison of Direct and Indirect Methods

	Number of		% Quartz	
	Filters	Analyses	Mean	Std. Dev.
Direct-on-Filter				
Site 1214140	11	27	28.4	3.8
omitting outliers	10	25	28.6	3.0
Site 1224166	11	25	22.3	3.5
omitting outliers	11	23	22.9	2.9
Transfer				
Site 1214140	6	6	26.6	3.4
Site 1224166	6	6	20.0	6.8
omitting outliers	4	4	24.0	3.2

TABLE VI
Laboratory Techniques

Technique	A	B	C	D	E	F	G	H	I
					Laboratory				
Direct-on-filter									
Silver (Ag)	Y	Y	Y						
DM				Y					
Transfer									
Ashed					Acid			LT^{A}	LT
Dissolved							Acetone		
Sonificated						Y			
2nd filter					PVC	DM	Ag	Ag	(KBr)
Radiation									
XRD	Co	Co	Cu		Cu		Cu		
Monochromator^{B}	G	G	LiF				G		
IR				Y		Y			Y
Line									
1,0,0^{D}	In^{C}				Y		Y		
1,0,1	Y	Y	Y		Y		Y	Y	
1,1,2	Y						Y		
2,11	Y								
Match^{E}	Y								
Absorbtion correction	Y^{F}							Y	
Chart recorder			In	Y		Y	Y		Y
Step scanning	Y	Y			Y			Y	
Peak height			Y				Y		
Peak area	Y	Y		Y	Y			Y	
Calibration									
Minusel-5					Y	Y		Y	Y
Airborne							Y^{G}		
(silica sand)	Y	Y		Y					
Cost/sample^{H}	20					40		55	

[A] L.T. low temperature asher.

[B] G is graphite.

[C] Interference.

[D] XRD Miller indices

[E] Program takes mean of first two lines in agreement.

[F] An absorption correction becomes significant for similar samples heavier than 3 mg, but not applied here because no light samples were collected from the same batch of silver membrane filters.

[G] Quartz used, not defined.

[H] Costs given in local $ Can. or U.S. as appropriate.

such as acid ash, which could reduce the interference and absorption from iron minerals on these and possibly other samples. However, there seems a possibility of substantial dust loss in the transfer process.

Radiation

There seems little to chose between XRD and IR based on these very limited results. In XRD either copper or cobalt Kα-radiation is used. Copper radiation is strongly absorbed by iron, the major mineral in these samples, and a diffracted beam monochromator and absorbtion correction are more significant than with cobalt radiation.

Conclusions

In total this report suggests that the Canadian and U.S. methods of quartz analysis using either XRD or IR are in reasonable agreement. However, comparisons of samples collected at many sites are required to determine the respective merits of the sampling and analysis systems.

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3.19

Section 3 - Chapter 19

Generation and Control of Mine Airborne Dust.

by

G. Knight

CANMET Report 80-27E.

Energy, Mines and Resources Canada

Ottawa (1980)

GENERATION AND CONTROL OF MINE AIRBORNE DUST

by

G. Knight*

ABSTRACT

A study was undertaken to determine the sources of airborne dust in mines and to investigate control methods. Experiments have identified three airborne dust types and their sources: mineral dust from all mining processes, oil mists from lubricating oil used in compressed air-powered machines, and particulates from diesel exhaust. Rock breaking and dust dispersion were studied and results showed that the dust produced is directly dependent on the total breakage and that dispersion increases by the extent of the handling, the energy expended in creating new breakage, the kinetic energy of the rock itself, and the velocity and turbulence of the air.

Two main dust control methods are wetting and ventilation. The effectiveness of wetting depends on wetting time, rock surface properties, type of wetting agent, use of steam and on the extent of mechanical mixing; sprays are ineffective in removing fine dust that is already airborne. Controlling dust through ventilation is effected by adding air to dilute the dust concentration, exhausting or drawing dust-entrained air from the workers' zone, and by controlling airflow direction.

The CAMPEDS gravimetric dust sampling system was used for measuring the amount of dust produced and gave total respirable dust, respirable combustible dust, respirable mineral dust (ash), and respirable quartz dust. Dust measurements from six mines are given in tabular form for blasting, rock loading, transport and hauling, drilling, and ancillary operations. Results showed that blasting, crushing and vertical orepasses produced the most dust. Evacuation of personnel from the mine for a sufficient time for the dusty air to leave or settle reduces exposure to dust from blasting. Crushing and orepasses can be enclosed and human exposure avoided. In mining areas, ore handling rather than drilling as might be expected was responsible for creating most of the dust.

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Two sets of experiments were made to investigate the effect of water on dust control in LHD loading operations, locations where good wetting and ventilation are essential. It was found that wet processes in milling operations produced substantial dust and that enclosures and extraction could substantially decrease general ventilation requirements.

Recommendations are given for dust control in hard rock mines for blasting, rock handling and drilling; suggestions are made for further studies on improving loading, floor smoothing, bucket handling, wetting, use of dust filters on mobile machines and high volume exhaust systems.

FORMATION ET MAÎTRISE DE LA POUSSIÈRE DANS L'AIR DE LA MINE

par

G. Knight*

RÉSUMÉ

Une étude a été entreprise afin de déterminer les sources de poussière dans l'air de la mine et d'examiner des méthodes de maîtrise. Les essais ont permis d'identifier trois sortes de poussière et leur source: la poussière minérale provenant de l'exploitation minière, les émanations d'huile lubrifiante utilisée dans l'équipement pneumatique et les particules de gaz d'échappement diesel. L'abattage de la roche et la dispersion de la poussière ont été étudiés et les résultats ont démontré que la quantité de poussière produite est fonction directe de l'abattage total et que la dispersion augmente selon le nombre de manipulation, l'énergie requise pour effectuer l'abattage, l'énergie cinétique de la roche même et le mouvement de l'air.

Les deux principales méthodes de réduction de la poussière dans l'air sont l'humidification et l'aération. L'efficacité du procédé d'humidification dépend du temps consacré à l'humidification, les propriétés de surface de la roche, le genre d'agent d'humidification, l'utilisation de la vapeur et l'importance du mélange mécanique; les vaporisations ne sont pas efficaces contre les poussières fines déjà dans l'air. L'aération peut réduire la concentration de la poussière dans l'air soit en ajoutant de l'air dans la mine pour en diluer la concentration, en aspirant l'air poussiéreux du milieu de travail des mineurs et en contrôlant la direction des courants d'air.

Le système gravimétrique d'échantillonnage de la poussière CAMPEDS a été utilisé pour mesurer la quantité de poussière produite et a fourni les données sur la poussière respirable totale, la poussière combustible respirable, la poussière minérale respirable (cendre) et la poussière de quartz respirable. Les lectures obtenues sur la poussière provenant de six mines ont été disposées en tableaux représentant les opérations de tirage, de chargement et de transport de la roche, de forage et autres opérations auxiliaires. Les résultats indiquent que les opérations de tirage et de forage et les galeries de soutirage verticales produisent le plus de poussière.

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L'évacuation du personnel suffisamment longtemps pour permettre à l'air poussiéreux de s'échapper ou se déposer, réduit leur exposition à la poussière générée par le tirage. Les galeries de soutirage et les opérations de concassage peuvent être isolées ainsi évitant l'exposition des humains. Dans les zones d'exploitation minière, la manutention du minerai plutôt que le forage tel que prévu, était responsable de la génération de la majorité de la poussière.

Deux séries d'essais ont été effectuées pour étudier l'effet de l'eau sur la maîtrise de la poussière dans les opérations de chargement, endroits où il est essentiel de maintenir une bonne humidification et une bonne aération. On a découvert que les procédés humides dans les opérations de broyage génèrent une quantité importante de poussière et que des enclos et l'extraction pourraient réduire considérablement les exigences générales d'aération de la mine.

Les recommandations sont données pour maîtriser la quantité de poussière générée dans les mines de roche dure par le tirage, la manutention et le forage; on y suggère la poursuite d'études sur l'amélioration du transport, le polissage du plancher, la manipulation du godet, l'humidification, l'usage des filtres à poussière sur les appareils mobiles et des systèmes d'échappement à haut rendement.

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INTRODUCTION

Dust has long been a major health hazard in the mining industry. There has even been evidence of silicosis in Stone Age flint workers.

This report forms part of the department's program to develop technology to solve problems related to underground mine workers' exposure to airborne, and thus respirable, dust produced by various underground mining operations.

Studies were undertaken at the Mining Research Laboratories at Elliot Lake to determine the sources of fine, potentially airborne dust in mines and to develop control methods capable of reducing dust levels significantly below provincial and federal standards. Dust production measurements by the Elliot Lake Laboratory staff were taken with the CAMPEDS gravimetric sampling system to provide total respirable dust, respirable combustible dust, respirable mineral dust (ash), and respirable quartz dust.

Rock breakage, dust dispersion and rock cutting processes are described as well as control methods by wetting and ventilation. Recommendations for improving dust control in hard rock mines are given and suggestions made for further studies on improving loading, floor smoothing, bucket handling, wetting, use of dust filters on mobile machines and high volume exhaust systems.

The principles of dust generation and control are discussed in the following sections.

BREAKAGE

Dust is produced in all rock breaking processes except possibly when rock splits at a plane of weakness. In most processes examined the quantity of fine, potentially airborne dust was related to the quantity of coarser dust produced, that is, to the total amount of rock broken into finer sizes. Figure 1 shows the mean value and range of sizes of broken material from one mine for seven rock types subjected to tests in which 1-cm lumps were broken in a rotary crusher at a coarse and a medium setting. Size distribution was determined by screening and elutriation of airborne dust. The technique was intended mainly for examining the quartz content of airborne dust and will be described in a later report.

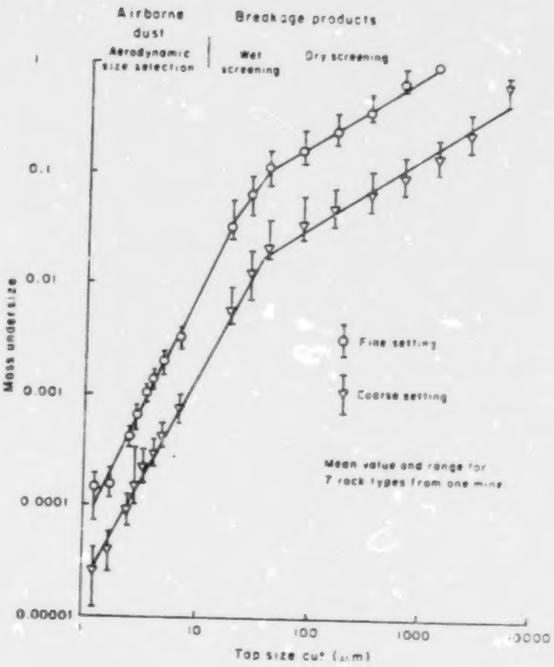

Fig. 1 - Size distribution of breakage products and airborne dust in laboratory test

Figure 2 shows the size distribution of fine dust obtained by optical microscopy transposed from number undersize to mass undersize (1). Discontinuities may occur in rocks with a marked grain size as shown in Fig. 3 (1). Such discontinuities are most often found in sedimentary rocks with strong grains in a weak matrix. However this does not alter the fact that the amount of potentially airborne dust is directly dependent on the total breakage. Generally, breakage is directly proportional to the energy input and inversely to the rock strength. Table 1 shows the estimated quantity of potentially airborne dust in the respirable size range when rock is broken to various maximum sizes for transport assuming a uniform breakage procedure. Table 1 shows that a large increase occurs when the ore is broken into finer sizes.

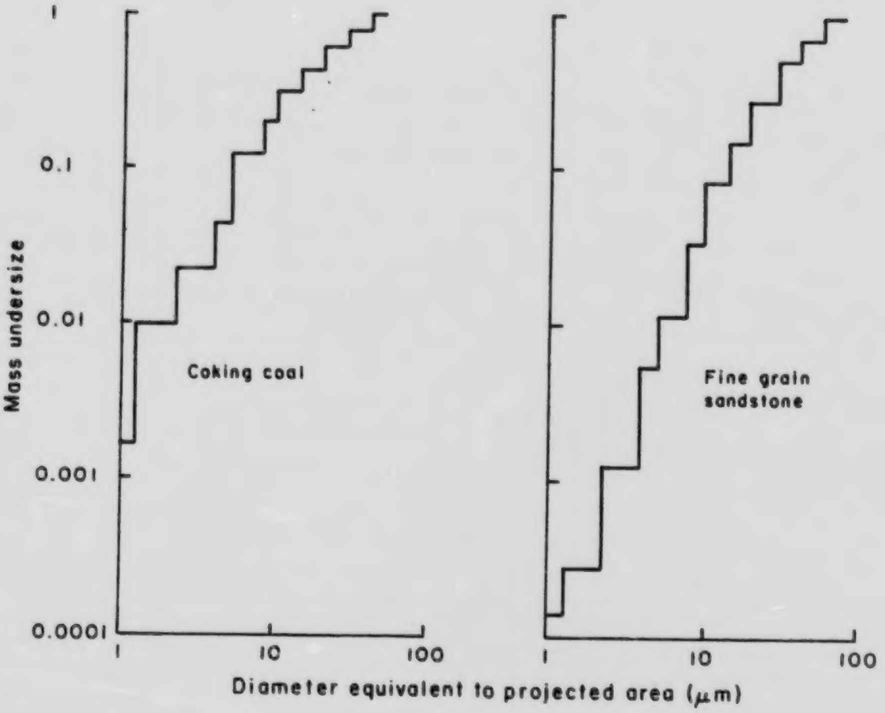

Fig. 2 - Size distribution of screened breakage products from compression test obtained using a microscope

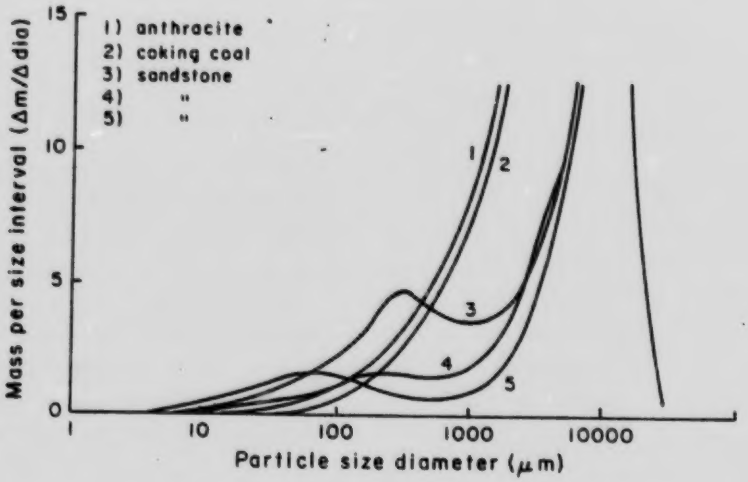

Fig. 3 - Mass distribution of debris from breakage by slow compression

DUST DISPERSION

Although all the fine potentially airborne dust could be dispersed by repeated handling in an airstream, generally, this occurs to only a proportion of it. Therefore, it is expected that in breaking dry material, the dust generation and dispersion will resemble that shown in Fig. 4. For instance, in a simple shatter test in which 50-mm lumps were dropped 2 m onto a steel plate in a gentle airstream, less than 10% of the dust from a weak coal was dispersed compared with most of the dust from a strong coal (1,2). Presumably the stress relief from the stronger coal imparted more energy or speed to the broken products and increased dust dispersion. Test results suggest that dust was directly proportional to the energy input and independent of coal strength. In contrast, potentially airborne dust increased with decreasing coal strength.

It can be surmised that dust dispersed in handling processes increases by:

1. the amount of fine dust created in the breaking process
2. the extent to which the material is stirred up during handling
3. the energy expended to create new breakage
4. the kinetic energy imparted to the freshly broken dust particles by the stress relief in the material broken
5. higher air velocities.

ROCK CUTTING PROCESSES

Rock cutting processes are used in coal mining machines, rotary drills, percussion drills, etc. The characteristic of these machines considered here is that they separate chips of rock from the main mass. Although the term cutting is used, the actual mechanics of raising a chip from the solid is complex, involving impact, fracture propagation, etc. Generally, two processes must be considered - cutting of the chip and its removal from the site.

Table 1 - Estimated potential airborne dust from breaking massive rock to various sizes

Maximum size of broken rock (metres)	Potential airborne dust in respirable size range (1) (g/t)
1	19
0.75	23
0.5	31
0.25	50
0.1	105
0.05	290
0.01 (1/2 in.)	600

(1) The permissible dust concentration in air is of the order of 1 g/($m^3 \times 10^3$)

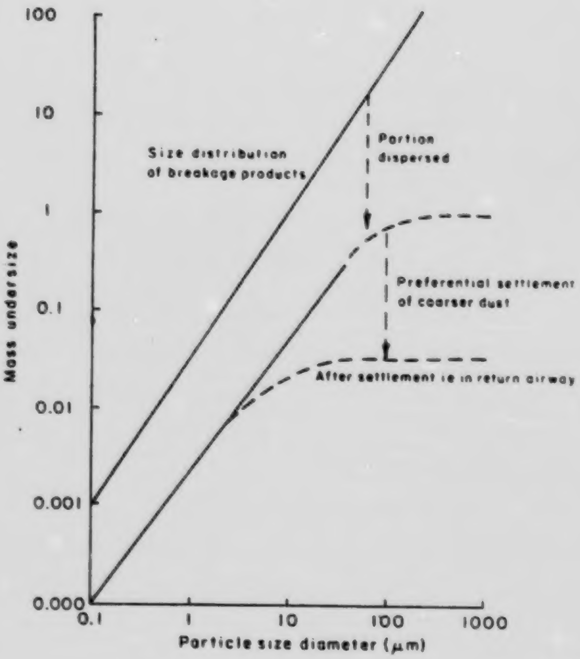

Fig. 4 - Development of the size distribution of airborne dust

In cutting it has been shown that the least amount of potentially airborne dust is produced when the chips are as large as possible. To achieve this, forces as high as possible must be applied to a small area and a depth of cut as large as possible made. The design of cutting tools to achieve these aims is complex, but minimum specific dust generation, i.e., dust generated per tonne, and minimum specific energy consumption are usually achieved together.

The problem of removing chips is most obvious in drilling where insufficient clearance or flushing agent may result in further breakage of the chips, in binding and resultant loss of energy from the drill rod, in decreased cutting speed, and increased specific dust generation and energy consumption.

DUST SUPPRESSION BY WETTING

Water is widely used in mines for dust control. Factors affecting dust suppression by wetting are:

1. Small potentially airborne dust particles can be attached to larger lumps and rendered non-dispersible by a thin film of liquid.
2. Water or other sprays are ineffective in removing respirable dust particles that are already airborne, unless very high accelerations are applied as in high pressure-drop wet scrubbers.
3. To be fully effective the liquid has to spread over the entire surface of the rock. The wettability of the rock depends on its surface properties and those of the liquid. Experiments have shown that most common rocks except sulphide minerals and coking coals are wettable.
4. It has been shown that it takes a long time for water to spread over the surface of a rock pile. Six samples of simulated run-of-mine material of 1 kg each and up to 4 cm in dimension were sprinkled with water and subjected to a shatter test after standing from 1 to 300 min (Table 2) (2).
5. Using wetting agents in water to improve wetting and dust suppression has been proposed. Laboratory experiments for which some results are shown in Table 3, indicate improvement, which suggest that (2):
   a. wetting agents reduce spreading time
   b. high concentration of over 1% is required
   c. the effect is most marked for difficult-to-wet rocks such as coking coals and sulphides
   d. the use of wetting agents in sprays reduces the size of droplets which can be obtained by increasing water pressure; no other measurable effect on the collection of airborne dust has been detected.

   However, mine trials have generally failed to show significant improvement in dust suppression. It is probable that this can only be obtained in certain types of operations, especially for minerals which are difficult to wet. It must be noted also that wetting agents may interfere with flotation processes used in ore preparation.
6. Obtaining a water layer by feeding steam into the rock pile is effective and decreases spreading time. Steam can be fed into moving

Table 2 - Dust raised from various materials after treatment with water

Material	Water addition level (*m* %)*	% dust dispersion time of standing (min) 1	5	30	300
Coal coking (301)	10	93	87	79	70
" bituminous (902)	10	82	61	50	35
" " (802/902)	10	-	50	32	20
Shale a	2.5	66	21	11	9
b	2.5	65	24	21	10
c	2.5	40	28	24	15

*m = mass

Table 3 - Effect of wetting agent solution on dust dispersion

Material	Wetting agent*	Addition level	% dust dispersion			
			Concentration of commercial agent			
		(m %)*	0(water)	0.2%	0.5%	2%
Coal coking(301)	(i)(anionic)*	10	89	66	29	2.1
	(ii)(non-ionic)*	10	-	-	-	1.4
	(iii)(mixture)*	10	80	52	15	1.0
Coal bituminous(902)	(i)	10	56	50	30	10
	(ii)	10	-	-	-	10
	(iii)	10	50	38	18	6.8
Shale a	(i)	2.5	21	-	-	13.8
	(ii)	2.5	24	-	-	27.8
	(iii)	2.5	28	-	-	27.8

*The greater efficiency shown for wetting agent (iii) than for agents (i) and (ii) appears to have been solely due to the greater concentration of active material in the commercial product.

rock in an enclosure at a transfer point on a conveyor belt.

7. Gentle mechanical mixing greatly speeds up the process of spreading water over the rock surface. In laboratory tests two minutes of mixing in a low-speed tumble mill was sufficient for full control as shown in Fig. 5. Mechanical mixing may effectively improve dust suppression on conveyor belts and during drilling.
8. It has been shown in rock and coal cutting operations and drilling that water is most effective when applied as close to the cutting point as possible and that this can be achieved by feeding water through the tool bit and onto the cutting face.
9. Feeding water to machines has two major problems: (1) the human one of ensuring that the water supply is connected and turned on which can be avoided by interconnecting the water valves to the power supply and (2) clogging due to dirt and pipe scale for which it has been recommended that spray orifices have a diameter of not less than 1.5 mm and be protected by filter screens on or close to the machine.
10. Muck should be kept wet during handling and transport because of long wetting times required when dry.
11. Most liquids are effective dust suppressants. Oils and salt solutions have been used specifically to avoid drying or freezing. Drying of settled dust in underground roadways has been prevented by using hygroscopic salt as a binder. Freezing of wet ore during surface transport in winter has been reduced by oil or salt solutions.

DUST CONTROL BY VENTILATION

Ventilation can control dust by: adding air to dilute the dispersed dust; exhausting or drawing dust-entrained air away from the operation to prevent it from reaching workers, and controlling airflow direction.

It is usually assumed in dilution ventilation that an increase in airflow will lead to a corresponding reduction in dust concentration,

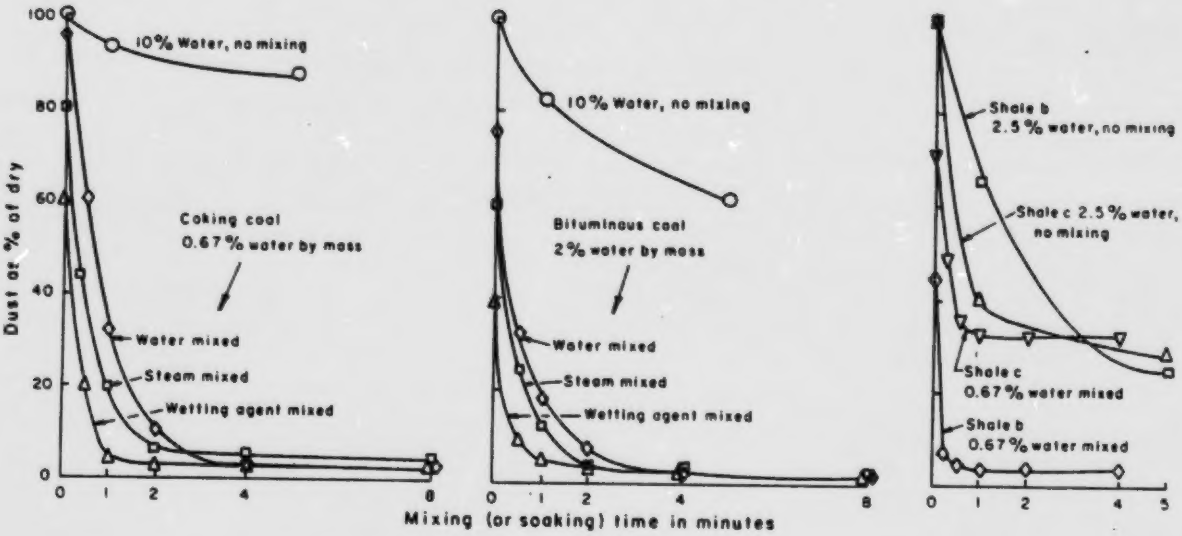

Fig. 5 - The effect of mechanical mixing or soaking after the addition of water, steam and 2% wetting agent solution

i.e., doubling airflow will halve the dust concentration. However this is not entirely true as the decrease in dust concentration is usually not as great as the increase in ventilation. It has been shown on English and German longwall coal faces that respirable dust concentration decreases with increased airflow at low velocities, reaches a minimum at 3 to 6 m/s and increases at higher velocities. Presumably increased air velocity tends to stir up the dust and disperse it, eventually off-setting the increased dilution.

Exhaust ventilation is effective when the dust source is enclosed and sufficient dust-laden air is drawn out to entrain the dust and prevent it from reaching the workers. For this, air must have sufficient velocity to pick up and retain the dust. A velocity of 1 m/s at the entrance to a hood is usually considered suitable for design purposes. However, higher values may be necessary if the ambient velocities exceed 0.5 m/s or if material moves out of the enclosure as on a conveyor belt. The exhausted air can be either passed directly to a return airway or filtered and returned to the ventilation circuit.

The quantity of air required for dust control in exhaust ventilation is decreased by:

1. reducing openings in enclosures to a minimum
2. proper maintenance of enclosures
3. lowering general air velocities
4. decreasing air turbulence from moving parts or from material within or leaving enclosure
5. avoiding pumping effects, i.e., rotating or moving components can act as fans pushing air out through holes in enclosure against pressure developed by the exhaust fan.

Exhaust ventilation generally requires much smaller volumes of air than dilution ventilation to control dust concentrations.

Airflow direction is mentioned in most manuals as a means of controlling dust but these generally do not emphasize its possibilities. Basically, it can have an intermediate effect between that of dilution and exhaust ventilation. In underground mining where airflow is necessarily controlled, dust exposure may be greatly reduced by ensuring that air from dusty operations passes directly to return airways and that most work is done on the intake side. For instance, stope drilling and mucking should be planned so that drillers are not exposed to dust from mucking and the mucking machine should be operated from the air intake side.

A two-to-one difference in the dust exposure of two men working in a development heading was found in one study over four sampling days. Presumably this was due to one man preferring to work in the stream of high velocity fresh air coming from the duct whereas the other did not.

Diffuser nozzles have been used on high speed ventilation ducts to supply a comfortable stream of clean low-velocity air to workers.

DUST MEASUREMENTS IN MINES

For discussion purposes, hard rock mining consists of:

1. separating ore from surrounding rock and breaking it into pieces small enough to transport
2. loading
3. transporting and handling
4. drilling
5. ancillary operations.

DUST MEASUREMENT TECHNIQUE

"Dust production" is the term most descriptive of dust generation and dispersion into the air at a mining operation. Dust was measured by the Elliot Lake Laboratory staff with the CAMPEDS gravimetric dust sampling system (3). The samplers operate over a full shift and have a two-stage impaction respirable dust size selection. Samples were collected on silver membranes and were weighed three times to give tare mass, gross mass and mass after ashing. They were further analyzed by X-ray diffraction for mass of quartz. These measurements gave four assessments:

1. total respirable dust
2. respirable combustible dust (defined as loss in mass on ashing at 500°C)
3. respirable mineral dust (ash)
4. respirable quartz dust.

Possible minor damage to the filter when loading and unloading the sampler can lead to large errors in estimating the mass of total respirable dust. This occurred particularly on the light samples in most of these studies and frequently caused difficulties in estimating the respirable mineral dust, which should equal total minus combustible, and the percentage of quartz in the dust. Note however, that the quartz measurement is absolute and is an order of magnitude more sensitive and accurate than weighing.

To facilitate comparison between mines, estimates of respirable mineral dust production were made from the quartz measurements and from the average value of the quartz content in heavy ashed dust samples, as well as from the measured difference between tare and ashed masses.

Sampling stations were set up in the airways both upstream and downstream from each operation. The stations were chosen to give the most uniform mixture of dust and air possible. Replicate samplers were strategically placed to obtain best readings without obstructing passage for men and vehicles. The samplers were kept running after the operations stopped to allow time for the dust to pass the return station. Airflow measurements were made at the stations and a recording anemometer was used to observe changes in airflow and to assist in estimating the total air volume passing each station.

Total dust produced at each operation was determined by multiplying the dust concentration at each station by the total corresponding airflow and subtracting the resultant figures at the intakes from those at the returns. This figure was then divided by the unit of production - tonnes of ore, length of hole drilled, or other unit as applicable - to give specific values per unit of production.

DUST PRODUCTION MEASUREMENTS

The measurements from six mines over the last five years are summarized below.

Blasting

Measurements were made on airborne dust

reaching surface after production blasting between shifts and underground after blasting in a stope and heading, and after secondary blasting in a drawpoint (Table 4).

It is difficult to measure dust produced in a blast because of disturbance to the airflow. The apparent differences between the four results in Table 4 need further study to better understand the factors involved. Future studies should determine the energy input from the explosives in at least a semiquantitative form.

Clearly, blasting in hard rock mines produces large quantities of dust, emphasizing the importance of evacuating men and allowing adequate time for ventilation to remove dust and fumes.

Loading

The following equipment was used to load broken rock for transport (Table 5):

1. rail-mounted compressed air-powered mucker emptying into a rail car in development headings
2. electric and compressed air-powered slusher operating in drifts and stopes (2a,b,c)
3. diesel-powered load-haul-dump machines (LHD) of various sizes operating in headings and drawpoints (3a,b). In some cases LHD's loaded the rock into diesel-powered trucks. A separate measurement of dust produced in this transfer was not possible because the layout of the heading and the ventilation system prevented selecting sampling stations with adequate mixing of dust with air.

It can be seen that rock loading produces substantial mineral dust. The electric-powered slushers produced negligible combustible dust. The compressed air-powered equipment produced measurable quantities, presumably of lubricating oil mist, and the diesel-powered equipment produced large quantities of combustible dust.

The quantities of mineral dust varied substantially from one site to another for which a number of factors were responsible:

1. Wetness of rock - although water was always used, apparently not all of the rock surfaces were wetted.
2. Roughness of floor - it was apparent that loading was more difficult and presumably more dust was produced on rough floors than on smooth.
3. Clean up and scaling - loading machines used for clean up at two sites produced much more dust per tonne of muck than normal loading operations.
4. Operator finesse - some drivers, especially on lower-powered machines, developed techniques for rapid loading, presumably with low energy input and low dust production.

Rock Transport and Handling

After loading, rock is transported horizontally and vertically for considerable distances to surface, usually via an underground crusher. A limited number of such operations were examined (Table 6):

Table 4 - Blasting

Site	Airflow (m^3/s)	Tonnes	Sampling period (min)	Number of tests	Respirable dust production (mg/t)			
					Total	Combustible	Mineral	Quartz
Total mine	450	2900	210	1	1200	540	450	300
Steep stope	2.5	180	330	1	2100	600	1400	700
Flat heading	20	270	360	1	1800	1400	300	150
Secondary 6 oversize rocks	7	6	30	1	9	-	700	70
Mean					1500	900	750	-

Table 5 - Loading of rock

Site	Operation	Airflow (m^3/s)	Tonnes	Sampling period (min)	Number of tests	Respirable dust production (mg/t)			
						Total	Combustible	Mineral	Quartz
1	Mucker in heading								
	range	1.5-3	60-90	210-330	3	40-200	12-180	14-42	7-21
	mean	2	75	260		90	80	24	11
2a	Slusher in raise								
	range		30-50	69-150	3	0-50	0-6	8-80	4-39
	mean	1.5	35	95		18	2	35	18
2b	Slusher in stopes								
	range	0.6-4	50-200	220-280	4	11-150	0-10	40-170	20-84
	mean	3	80	250		60	7	80	40
	range	.5-1.5	60-80	210-270	4	60-500	90-250	100-250	10-110
	mean		40	250	4	180	120	90	45
2c	Slusher in stope								
	range	0.7-1.3	60-100	-	4	80-250	30-45	40-200	20-53
	mean	1	80			140	35	110	30
3a	LHD in heading								
		0.6	500	-	1	136	43	100	43
	mean				3	750	450	180	20
	range	10	200	100-180	9	225-980	240-450	100-400	29-315
	mean	10	200	140	1	600	360	240	103
3b	LHD in drawpoint								
	range	3.5-8	250-500	90-345	4	200-450	170-280	50-200	14-39
	mean	6	350	245		270	200	110	30
	range	1-17		100-350	5	260-3000	230-350	150-1300	15-130
	mean	5	160	250			270	550	55
Overall range of test means								24-550	
Overall mean								140	

Table 6 - Ore handling

Site	Operation	Airflow (m^3/s)	Tonnes	Sampling period (min)	Number of tests	Fall (m)	Respirable dust production (mg/t)			
							Total	Combustible	Mineral	Quartz
1	Loading mine cars	3-73	140-420	30-114	2	3	35	15	70	8
2	Dumping on grizzly	70	800	300	1	1-3	270	-	54	27
3a	Orepasses	40	2000	320	1	300	700 (1)	low	800 (1)	400
b	Orepasses	1	200	120	1	30	105	7	70	16
c	Orepasses									
	top level, mean	40	600	200	3	300	270	90	180	18
	182 m down, mean	25	1600	140	7	300	250	80	160	16
4a	Underground crusher	3	2400	325	2	3	600	20	800	400
b		3	800	200	1		200		250	130
c		2.5	200	120	1	3	100		60	15
d		3	750	390	1	3	150		90	22
5	Big rock	3	20	390	1	3	110		35	10
6	Skip loading	5	514	210	1	6	115	15	30	16

(1) Lower total than combustible assessment is an indication of the weighing errors

1. Filling rail cars from a chute with a free fall of 1 to 2 m
2. Dumping rock onto a grizzly from diesel-powered LHD's and trucks. This operation included breaking oversize pieces with an hydraulic pick. The measured dust was not the total produced but only that part escaping the local exhaust system below the grizzly and from the filter system.
3. Nearly vertical ore and waste passes.
    a. This system had dump points every 35 m vertically with interconnections between ore and waste passes at each level; an exhaust system drew dusty air from the lowest level.
    b. The part of this system examined consisted of a 30-m section of orepass with fingers at top and bottom; the free fall of material induced airflow out through the lower finger.
    c. The system consisted of a 600-m vertical orepass with dump points at the top and at 120-m intervals; dust leakage from the top was calculated on tonnage from this level and at the second level on tonnage from both upper levels.
4. Underground crushers; although total dust was measured on systems a and b, only that leaking from the crusher and air exhaust system with filter was measured on c and d; at two other crushers, dust leakage could not be estimated because of low ventilation rates.
5. Big rock handling; rocks too large for the crusher were handled at this mine by a crane and dropped into a side heading for secondary blasting.
6. Skiploading; one skiploading facility fed from an orepass was examined.

Most ore handling operations produce large quantities of dust and many achieve partial or complete dust control through exhaust air systems.

Drilling

Drilling is a major operation in most hard rock mines and uses a substantial proportion of the total manhours. Before the advent of wet drilling it was considered the most hazardous occupation leading to silicosis.

Five drilling systems were studied as shown in Table 7. Dust production is given as mg/m of drillhole.

1. Jackleg compressed air-powered rotary percussive drills; these data could not be separated from drilling for roof bolts using a stoper; dust production is given in terms of total length of hole; bit diameter was about 40 mm.
2. Bar and arm compressed air-powered rotary percussive drills; these drilled long holes of about 50 mm in diameter.
3. Jumbo-mounted compressed air-powered rotary percussive drills; bit diameter was about 50 mm.

Table - 7 Drilling

Site	Operation	Airflow m^3/s	Metres	Sampling period (min)	Number of tests	Respirable dust production mg/m			
						Total	Combustible	Mineral	Quartz
1	Jackleg								
	range	0.1-5	40-150	65-310	10	0-50	0-45	0-3	1.5
	mean	2	105	224		9	8	1.2	0.6
	range	4-8	60-110	145-250	5	0-12		0-3	1.5
	mean	6	85	200		2.4		.6	.3
	mean	0.6	120	200	3	4	1.2	L	L
2	Bar-arm mean	1.5	180	153	2	20	15	3	.6
3	Jumbo								
	mean	1.7	300	300	2	4.5	3	1.5	.3
	range	8-18	130-290	140-285	5	L-40	L-33	L-5	L-2.5
	mean	10	180	225		20	18	1.8	1
	mean				2	15	15	L	L
4	Mini borer				2	85 (8)*	6 (0.6)*	3.5 (0.35)*	1 (0.1)*
5	Down the hole								
	range		46-120		4	120-1000	60-700	60-350	16-110
	mean		80			450 (90)*	350 (70)*	100 (20)*	50 (10)*

*Values in brackets are those for equivalent length, by rock volume removed, in 50-mm diameter hole

4. Mini borer; rotary drill, drilling down-holes of about 150 mm in diameter.
5. Down-the-hole drills; four compressed air-powered rotary percussive drills were used in the same stope for which the total production was measured on four separate shifts; bit diamter was 110 mm.

Table 7 indicates that all drills except the down-the-hole were characterized by low dust production. This made it difficult to measure the increase in dust concentration between intake and return air except at low rates of airflow.

The down-the-hole drills produced copious quantities of airborne dust because compressed air was used as the flushing agent. Although some water was used it was apparent that dust control was less effective than with any other drill even allowing for the greater quantity of rock broken per metre of hole.

Ancillary Operations

A few ancillary operations were examined for which production results are given in Table 8:

1. Drill preparation. At this particular section of the mine a 5-t capacity LHD unit was used to clean up muck left by a similar 8-t unit on production and to scrape the face ready for drilling. The dust produced per ton of muck based on the number of buckets dumped was ten times greater than in production mucking. This was partly because the muck was not properly wetted and partly because of the high energy expenditure in removing cracked rocks from the toe of the face. This half-hour operation which took place with the drill operators present produced as much dust as a 3-boom drill jumbo in two or more shifts.
2. Back filling. Back filling with fine hydraulically transported mine waste was examined on one shift. The dust was produced in the stope.
3. Conveyor belt. Two conveyor belts about 60 m long with loading chutes each carried 330 t/h. The rock was left dry to avoid freezing. Dust production was high even though the loading points were properly enclosed.

Table 8 - Ancillary mining operations

Site	Operation	Airflow (m^3/s)	Tonnes	Sampling period (min)	Number of tests	Respirable dust production (mg/t)			
						Total	Combustible	Mineral	Quartz
1	Drill preparation (ST 5)	10		30	1	1800	1000	800	400
2	Back filling	2.5	800	180	1	270	-	-	-
3	Conveyor belt	4	4000	360	12	23	1	14	5
4	Autogenous mill	2	2000	360	2	65		27	9
5	Pebble mill	2.2	500	360	2	5		11	4
6	Magnetic separator	.2	320	360	2	1		1	3
7	Flotation	.2	320	360	2	3		2	7
8	Balling drum	2.7	400	360	1	13		13	-

Operations 4 to 8 in Table 8 were in a surface mill processing iron ore. Even though all the processes were wet, substantial quantities of dust were produced. Operations 4 to 7 could be readily enclosed and dust emission controlled by a low airflow exhaust system rather than by conventional higher airflow dilution ventilation.

SUMMARY OF DUST PRODUCTION

Clearly, gravimetric assessments show that rock handling is a much greater hazard than the historically hazardous operation of drilling. Although partly due to the parameter change from number to mass for the finer dust in drilling compared with other operations, the main factor is the effective dust control achieved by feeding water to the bit. It should be noted that the down-the-hole drill used compressed air with only a little water added to flush chips from the hole and produced much larger quantities of respirable dust than any other drill, even allowing for the larger hole size.

In most of the mines examined the major mineral dust exposure was due to loading. Secondary blasting in the mining area or substantial contamination of the intake air by the ore transport system was equally important in some mines.

Mine transport systems can produce large quantities of mineral dust but effective control has been achieved by entraining dust from non-mobile operations in an airstream and filtering or directing it to a return airway.

Table 9 shows the estimated dust production for the mine where most of the experimental work was undertaken. This mine operated at depths between 240 and 600 m using horizontal track drifts and stopes on the 2- to 6-m thick ore horizon with jackleg drills and electric slushers.

Table 9 - Estimates of total dust produced for one mine shift

Operation	Tonnes	Respirable dust production g/shift				Mineral dust as % of	
		Total	Combustible	Mineral	Quartz	Entire mine	Mining area
Between shift main blast	2700	5600	2800	2600	1300	34	
Mining area							
Secondary blasting	100(1)	100	20	80	40	1	15
Slushing	2400	350	20	330	165	4	63
Mucking	400	40	30	10	5	0.1	2
Car loading	2700	115	60	56	27	0.7	10
Drilling	2700 (2200 m)	22	20	3	1.5	0.04	0.6
Scaling etc.(2) -		10	-	10	5	0.1	2
Total		637	150	487	243	5	100
Outbye							
Rail transport	2700	65	60	5	2	0.1	
Dumping into orepasses(2)	2700	60	10	50	25	7	
Orepasses	2700	2700	60	2600	1300	34	
u/g crusher	2700	1800	-	1800	900	23	
Skip loading	2700	160	40	100	50	1.3	
Total		6800	170	4600	2300	60	
Entire underground mine		11000	3100	7700	3850	100	

(1) Estimates based on a guess as to variable secondary blasting carried out.

(2) Estimate.

The ore output was 2700 t/shift and production blasting was carried out between shifts.

It can be seen that most dust was produced in the ore transport outbye of the active mining area, where in this particular mine the orepasses are near the shaft and away from the extraction area. The main dust sources were well controlled by exhaust ventilation and only a small proportion of the transport dust leaked into the working areas and travelways. The production blast was the next major source and exposure was avoided by blasting between shifts.

The mineral dust production in the active mining areas is only about 5% of the mine total. Most of this arises from handling with only little from drilling.

In a second mine where a nearly vertical orebody is worked by diesel-powered LHD's on tramming levels and the nearly vertical orepasses are placed close to the intake airway so that dust leakage can spread over most of the mining zone, an analysis was made of the sources of dust to which the LHD operator was exposed (Table 10). It can be seen that the operator's chief source of exposure occurred during the 15% of his shift when he was in the short heading to the orepass dump point*. A further 12% of his dust exposure was due to dust leaking from the orepasses into the intake air leading to the drawpoints. This leakage also forms a major part of the dust exposure of the other miners on this level. Loading was responsible for only about 10% of the operator's total dust exposure. His vehicle's diesel engine was responsible for about 30%.

DUST CONTROL EXPERIMENTS

It was shown previously that loading is one of the dustiest operations to which miners are exposed. To date two sets of experiments were made to investigate the effect of water control on dust in LHD loading operations. In the first set carried out in a drawpoint in high sulphide ore, loading was carried out dry or with 1-, 2-, or 4-bar pattern sprays arranged as shown in Fig. 6. In the second set, muck piles in headings six or more metres wide were examined using various wetting times with simple jets from hand-held or blocked-in-position hoses and nipples.

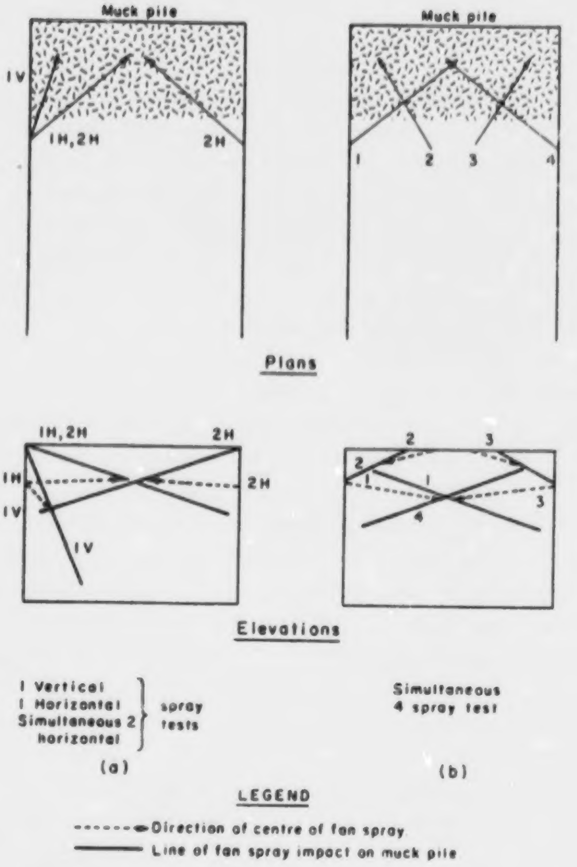
Muck pile
IV
IH,2H
2H
Muck pile
1
2
3
4
Plans
IH,2H
2H
IH
2H
IV
IV
2
3
2
1
1
3
4
Elevations
I Vertical
I Horizontal
Simultaneous 2 horizontal
spray tests
(a)
Simultaneous 4 spray test
(b)
LEGEND
Direction of centre of fan spray
Line of fan spray impact on muck pile

Fig. 6 - Configuration of water sprays for wetting tests in drawpoint

Results from the first set, based on differences between return and intake as well as between drawpoint and intake air samples, are given in Table 11. Problems occurred in assessing

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*The mine has since improved dust control in the orepass by installing level connectors and exhaust fans.

Table 10 - Analysis of LHD operator dust exposure

Operation	Cycle time (seconds)	Respirable dust concentration mg/m^3 Combustible	Mineral
Loading	40	2.8	4.0
Tramming	240	1.2	0.7
Dumping	60	1.2	10.0
Total	340		
Mean		1.38	2.72
Dust source		**% dust attributed to source** Combustible	Mineral
Diesel engine		30	0
Loading			10
Dumping			43
Orepass leakage			12
Other		3	2
		33	67

Table 11 - Effect of water on LHD loading high sulphide ore

Sprays		Respirable dust production (mg/t)				Relative respirable dust production (ng on filter/bucket)				Dust as % of dry	
No.	Dir	Total	Combustible	Mineral	Quartz	Total	Combustible	Mineral	Quartz	Combustible	Quartz
	dry					50	19	22	6		
	dry	280	330	21	59	63	42	21	8		
1	hor	-180	-123	-5	-14	13	1	12	3		
1	vert	33	180	58	18						
1	hor	290	81	167	57	35	30	4	1		
1	hor	-20	71	-84	14	26	11	13	6		
2	hor	104	75	52	12	15	8	6	1.5		
2	hor	-114	35	-135	36	4	8	-4	1		
2	hor	29	32	-15	13		5	-	.5		
2	hor	15	3	54	4	7	-6	13	.5		
4	hor	200	130	110	13	3	-1	4	.5		
Means	dry	280	330	21	59	58	30	21	7	100	100
1	spray	18	50.15	47	20	30	20.67	8	3.5	60	42
2	spray	9	36.11	-11	16	9	4.13	5	.9	12	20
4	spray	200	130.40	110	13	3	-1.0	1.4	.5	20	15
Mean wet		61	76.23	26	21	15	8.27	6	1.6	25	30
Std dev		116	57	99	17	11	11	6	2		

Note: Negative values result when fan stabilizing airflow in tram drift also acted as dust remover and actually reduced dust concentration of return air below that of intake air. The relative respirable dust production figures were obtained by applying a correction factor assuming that the dust collector efficiency was constant.

dust production because of recirculation and dust collection by a fan introduced to stabilize the airflow, as well as by the relatively high dust concentration in the intake air.

It was clear that adding water decreased mineral dust production but not to the extent possible because dry muck was always visible immediately after loading.

Results from the second set of tests on highly siliceous rock muck piles are shown in Table 12. The first 16 tests were made on muck piles in various headings and represented normal mine operation. The last two tests were made on a similar muck pile at a site having through-ventilation. It was obvious that adding water substantially reduced dust levels to less than 20%. It was also evident in normal mine practice, especially during the first few buckets at the start of the shift in early start tests, that dry muck was frequently visible. The extra wetting tests in which loading of a muck pile was continued after the lunch break led to a further substantial reduction in mineral dust. The extra wetting consisted of the normal wetting before and during loading of the muck pile throughout the morning and afternoon as well as extra wetting by the dust survey team during the operator's lunch break.

The two tests showed somewhat erratic results on combustible dust production. Although adding water could affect ease of loading and power requirements or even modify the soot production by the engine, it is believed that the erratic results are probably due to the errors in assessing combustible dust being greater than those in assessing quartz dust, or to variation between engines.

COMPOSITION OF AIRBORNE DUST IN MINES

The experiments on dust production have identified three airborne dust types and their sources:

1. mineral dust from all mining processes
2. oil mists from lubricating oil for compressed air-powered machines
3. diesel exhaust particulates.

Mineral dusts are not all equally hazardous to health. Free silica minerals and mineral fibres (asbestos) are of an order of magnitude more hazardous than most other common minerals. Of the free silica minerals, quartz is the most common, and in this study was the only "more hazardous" mineral measured separately. In most mines tested the respirable quartz formed a constant proportion, within the limits of experimental error, of the respirable mineral dust. This proportion was always less than that in the rock mined. In one mine with a massive sulphide ore there was some evidence that the quartz content was higher in the airborne dust in the mining zone than in the crusher room. Presumably, by the time the rock reached the crusher the silicate components were well wetted and their dust was better controlled by the various water additions en route.

In jackleg drilling it was found that 90% of the dust collected on the filter was combustible. It was presumed but not proven that this was lubricating oil atomised by the high energy of the exhaust air. A simple calculation showed that the measured quantity of respirable combustible dust was about 0.33% of the amount of lubricating oil sent underground for use in drills.

The diesel exhaust particulates are a complex mixture of soot, unburnt hydrocarbons, partially oxidized hydrocarbons, and sulphuric acid. The sulphuric acid mist is produced by oxidation of some of the sulphur dioxide in the catalytic purifier, and may be absorbed onto the soot particles.

In this report only the total exhaust particulates as indicated by the respirable combustible dust, i.e., loss in mass on ashing, are considered.

Table 13 shows the composition of the dust produced at various operations and its probable source. In view of the limited number of operations examined, the extent of variation in composition is probably too low and the figures should be used only as an indication of the possible hazards.

Table 12 - Effect of water on LHD loading high silica ore

Description	Tonnes	Respirable dust production (mg/t)				Dust as % of dry	
		Total	Combustible	Mineral	Quartz	Combustible	Quartz
Normal mine practice							
	168	750	750	92	46		
	176	1300	1100	116	58		
	152	800	550	114	57		
	160	650	450	59	29		
	424	485	420	70	35		
	160	530	390	124	62		
	160	225	240	90	45		
	160	1090	470	630	315		
	216	460	380	80	40		
mean		700	525	150	75	105	25
Early start	128	900	750	200	100		
	32	750	600	170	85		
mean		825	675	185	92	135	31
Extra wetting	200	800	750	96	48		
	176	1500	1300	58	29		
	194	600	600	66	33		
	32	700		28	14		
mean		900	825	62	31	165	10
Dry test	120	900	500	600	300	100	100
Dry test after 1 1/2 hours wetting	88	800	700	110	55	140	18
Overall mean		780	625	160	80	125	27
Overall wet tests		770	630	130	65	125	22

Table 13 - Composition of airborne dust produced by various operations

	Ash	Mineral dust total	Combustible dust		
			Total	Oil mist	Diesel exhaust
	%	%	%	%	%
Blasting	88	50-70	12		
Loading					
C.A. mucker	25	25	75	75	
C.A. scraper	70	70	30	30	
Electric slusher	95	95	5		
Diesel LHD	20-40	20-40	60-80		60-80
Drilling	10	10	90	90	
Orepasses	100	100	0		
Crushing	100	100	0		

RECOMMENDATIONS FOR DUST CONTROL IN HARD ROCK MINES

BLASTING

Because of both dust and fumes, blasting should be carried out so that men are not exposed to contaminated air either in the area itself or to the air leaving it. Blasting techniques should aim at producing a minimum of fines and oversize lumps, and producing the smoothest floor possible (4).

ROCK HANDLING

Rock breaking produces large quantities of airborne dust, and although the broken ore needs further reducing, additional breakage should be minimized at all sites where men may be exposed and confined to such areas as crushers where enclosures and filtration can capture most of the dust. In handling rock, attention should be given to:

1. Minimizing free fall as the amount of dust produced is proportional to the distance dropped.
2. Using slides as sliding a given vertical distance reduces dust production compared with falling freely.
3. Making floors as smooth as possible to minimize energy required to pick up or drag rock.
4. Locating and designing sites for secondary breakage of oversize rock such as grizzlies or dumps, so that the dust dispersion can be entrained and either directed to a return airway or collected by filtration; in particular, they should not be located in main airways where high air velocity increases dust dispersion.
5. Vertical orepasses. These are a major source of dust because of the piston effect of falling rock pumping air out of the orepass into the work place. Pressures can be developed high enough to lift 1-cm thick steel plate doors.

Although pressure can be reduced by interconnecting ore and waste passes at each level, there will still be some leakage of dusty air and elaborate precautions may be necessary to divert this from the work areas.

Siting orepasses close to the return airways may be well worthwhile.

The use of off-vertical orepasses could possibly decrease dust production by transforming free falling to a sliding motion, decreasing fresh breakage. A controlled feeder can prevent the formation of plugs and greatly decrease the pumping of dusty air.

6. Wetting broken rock. This can prevent fine dust from becoming airborne by binding it to large pieces of muck. To be effective a thin liquid layer must cover all free surfaces in the rock pile. For the liquid to spread over the rock its surface must be wettable. Silica rocks are usually readily wettable whereas some sulphide minerals are not. Even for silica rocks, wetting times of more than two hours can be required to completely wet a muck pile and minimize dust dispersion during loading. For sulphide rocks wetting times may be much longer.

   The quantity of water required however is not great - a few tens of litres per tonne and the use of mist sprays applying water at a low rate evenly over the top of the muck pile for hours is probably most effective. A hand-held hose jet is usually not satisfactory and encourages inadequate wetting.

   The mechanical mixing involved in rock movement in orepass and crusher operations spreads the water much faster and quickly traps any dust created by new breakage.

7. Some ventilation is essential to dilute the dust concentration. Whenever possible, airflow direction should be such that the air flows away from workers towards the dust source.
8. Enclosure of dust handling operations is effective in decreasing air velocity over moving rock and reduces the dispersion of dust.
9. Where breakage is unavoidable, such as in orepass and crusher operations, enclosures and air extraction are almost always required for good dust control.

DRILLING

Normal wet drilling is not a substantial source of dust as the application of water close to the cutting edge and its virtual immersion in water in the hole prevents dust escape. However, large quantities of potentially respirable dust are formed so that dust control must be considered in any change in drilling technique, such as when going to down-the-hole drilling (Table 7).

LHD's, and probably other machines, when preparing faces for drilling apply high forces and expend much energy, thereby causing fresh breakage and creating more potentially airborne dust. The LHD bucket is thus a poor tool for cleaning faces and alternatives are required.

RECOMMENDATIONS FOR FURTHER STUDIES

Further studies are required to better understand the effects of floor roughness, loading techniques, wetting times and applying filtration devices to mobile equipment.

Loading of broken rock is still a major source of dust and four main approaches are recommended for further study:

1. Improving the loading process by smoothing the floor and by better bucket handling.
2. Devising better wetting techniques - wetting is time-consuming but requires little water. Studies are required to investigate:
   a. effects of wetting agents on sulphide ores and on subsequent flotation processes;
   b. mist sprays initiated by the blast and determining minimum wetting times for various types of rock and sizes of muck pile; integrating these into the mining cycle;
   c. techniques for wetting standing ore in stopes as wetting muck only at drawpoints cannot be fully effective because of the short exposure time; mist sprays are a possibility as is also extraction ventilation from each drawpoint;
   d. use of water stemming which introduces water directly into the blasted rock pile during blasting when rapid loading is essential.
3. Using small machine-mounted filters which are now being used successfully on coal cutting

machines. It is possible that filters and air exhaust systems could be mounted directly on LHD's to decrease both mineral and diesel exhaust dust. Because equipment is subject to abuse, components would have to be built in rather than added on, necessitating machine redesign. Other possible applications of such filter units would be on rock breakers, toe cleaning machines, down-the-hole drills, etc.

4. Improving ventilation techniques - most active mining sites produce substantial quantities of dust only when rock loading or scaling are in progess. The dust sources and breathing zones may be separated by enclosures or partitions or by controlling airflow direction:
   a. as well as low volume forcing systems consideration should be given to high volume exhaust systems which are turned on only when most needed during the dustier operations. This has obvious application in multiple drawpoint operation but is harder to apply in stopes and headings;
   b. studies should be made on the design and effectiveness of airflow direction control at the outlet of fresh air ducts, such as the use of diffusers to blow relatively low velocity air towards the workers' breathing zone.

DIESEL ENGINE EXHAUST PARTICULATES

Combustion engine-powered vehicles are attractive in mines because of their mobility and low ancillary support needs. As the diesel (compression ignition) is the main type of engine used and obviously produces substantial quantities of contaminants, reduced exposure is recommended as the health hazard has not yet been completely evaluated. Active research on control of exhaust pollutants is in progress elsewhere in CANMET (5).

ACKNOWLEDGEMENTS

The author wishes to acknowledge with thanks the kind cooperation and assistance of the management and other staff members of the mines who preferred to remain anonymous, but without whom this report could not have been prepared. The author also wishes to thank other employees of CANMET for their cooperation in gathering dust data and related information. W. Stefanich, the dust laboratory technician, was of great assistance in most of the field work.

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3.20

Section 3 – Chapter 20

Dust Control for Scooptram Operations

by

G. Knight

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Stoping Mines. edited by D. R. Stewart. pp 841–843
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and Petroleum Engineers Inc. New York (1981)

RÉDUCTION DE LA QUANTITÉ DE POUSSIÈRE APPLIQUÉE À L'UTILISATION DES WAGONS À GODETS

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RÉSUMÉ

Dans la plupart des mines, le principal facteur contribuant à l'exposition des mineurs aux poussières est lié à la manutention de la roche. On utilise fréquemment des wagons à godets, et ils produisent de 8 à 1300 mg de poussière inhalable par tonne de minerai chargé. Il est démontré que les appareils d'arrosage aux points de soutirage ne sont pas totalement efficaces pour le mouillage de la roche, et des suggestions relatives à des techniques de mouillage améliorées sont présentées. Des techniques pour une plus grande réduction de la quantité de poussière par ventilation et filtration locale sont décrites. Le problème des poussières provenant des tas de minerai et des dépôts aux niveaux de roulage est résumé.

Chapter 66

DUST CONTROL FOR SCOOPTRAM OPERATIONS

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ABSTRACT

n most mines the major contribution to the exposure of miners arises from rock hand- . Scooptrams are frequently used and pro- 8 to 1300 mg of respirable dust for each of ore loaded. It is shown that sprays at points are not fully effective in wetting rock and suggestions for improved wetting niques are given. Techniques for improved control by ventilation and local filtration described. The problem of dust from ore- es and dumps on tramming levels are outlined.

INTRODUCTION

ck handling is a major source of dust in rground mining, and loading is often the r contributor to miners' dust exposure in active ore extraction areas of the mine. irable mineral dust generation and dispersion the air have ranged from 8 to 1300 mg/tonne re with a mean of about 300 for scooptram rations (1). In contrast wet drilling pro- s less than 5 mg of respirable dust for each e mined in a stope.

cooptrams are often used for loading in ng and sub-level stoping. When the ore is ved from a drawpoint below the stope, dust ration tends to be high because of poor ting. Concentrations tend to be even higher use of the poor ventilation in the short d headings leading to the drawpoint.

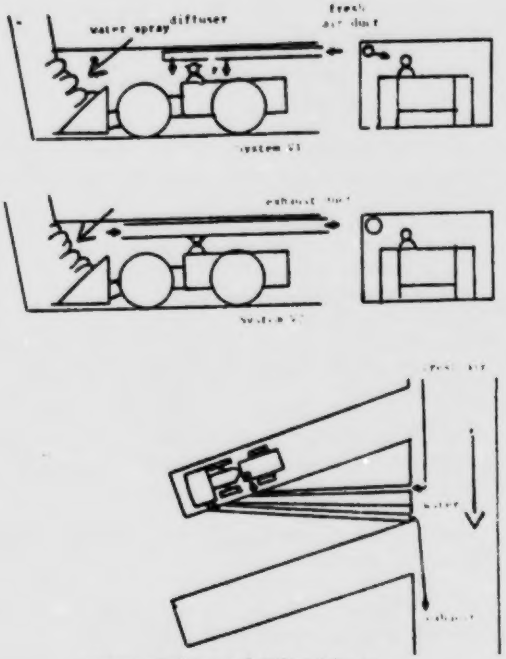
ome experiments on wetting with one to four ays showed improvement in dust control with reasing quantities of water but, even with r sprays, dry rock could still be seen on entry after the scooptram had left. The dust osure received by the operator during the rt period, 12% of the cycle, that he was in drawpoint amounted to 0.4 mg/m^3 averaged r the cycle.

This report discusses the dust controls ailable as well as those which could be tested r scooptrams operating in drawpoints. Atten- on is given to the exposure of both the erator and other men in the section.

DUST CONTROL AT DRAWPOINTS

Airborne dust at the drawpoint arises both om dispersion of fine dust already present and of fine dust produced in fresh breakage. Fresh breakage occurs both because of the ore falling and because of the crushing and chipping action of the bucket on the ore pile.

Wetting can be very effective in controlling dust already present if every surface of the rocks is wetted, but is not readily effective in controlling dust produced in fresh breakage. In the drawpoint wetting is not usually fully effective because of the limited time of contact with the normal heading mounted sprays, see Fig. 1.



Schematic showing use of drilled holes to avoid damage to tubing in drawpoint

FIGURE 1. Fixed drawpoint ventilation systems

Improvement might be obtained by drilling above the drawpoint into the stope. Experiments on this have failed because the water holes get plugged. In general, the ore stands in the stope for many days and methods of wetting it prior to loading could be investigated. The quantity of water required is relatively low 5 to 10 litres/ tonne spread out over the whole surface. In a near vertical stope it is possible that the application of a gentle mist over the surface of the pile for a number of days migh give better wetting without creating pockets of water which could rush out and form a hazard on the lower levels.

A second possibility is to add appropriate quantities of water during the blast by water loading of empty drill holes or other techniques. The mechanical mixing introduced by the blast should improve the spread of water through the rock.

Ventilation could also be used to improve dust control in the drawpoint. Probably two fixed ventilation methods could be used to achieve minimum dust exposure to the operator:

System V1: A forcing system discharging a gentle stream of fresh air through a diffuser into a breathing zone of the operator, Fig. 1.

System V2: Exhaust system drawing the dusty air from near the bucket, Fig. 1.

Because of the rough treatment in the heading by the bouncing scooptram during loading, better results might be obtained by using appropriate drill holes instead of ducting. One mine is already running the water line in a drill hole to minimize damage.

Machine mounted ventilation systems could also be used to minimize exposure to the operator.

System V3: A fresh or filtered air supply to a face mask or hood to protect the operator. Some mining companies have used or tested the following:

V3a fresh air supply from cylinders mounted on scooptram - solves the problem of exposure to gas too;

V3b filtered air supply from battery powered unit to face mask or helmet, such as an Airstream or Whitecap unit;

V3c filtered air supply from machine powered similar to V3b;

V3d filtered air supply to canopy over operator - machine powered.

System V4: A machine mounted and powered system which draws air from near the bucket, adds in the engine exhaust, and projects the air from the back of the machine to reach the airstream at the end of the drawpoint heading.

System V5: Similar to V4, but using a filter to collect the dust.

Improved wetting and all ventilation systems could reduce the operators' dust exposure, however, only improved wetting and Systems V2 and V5 have potential for reducing dust exposure to other workers in the vicinity.

DUST CONTROL AT DUMP POINTS

Usually at dump points the ore has been mixed with water during the loading operation and control of existing dust is almost complete, thus most of the dust dispersed into the air is fresh breakage and dust control can be achieved by minimizing free fall and the resultant fresh breakage. Free fall above the plane of the dump point could be minimized by operating the tilt and raise bucket controls together so that the lip of the bucket maintains a constant minimum height, rather than raising the bucket to the maximum then tilting as is common practice, see Fig. 2. This proposal would be facilitated by special interlocking of the tilt and raise controls for unloading the scooptram.

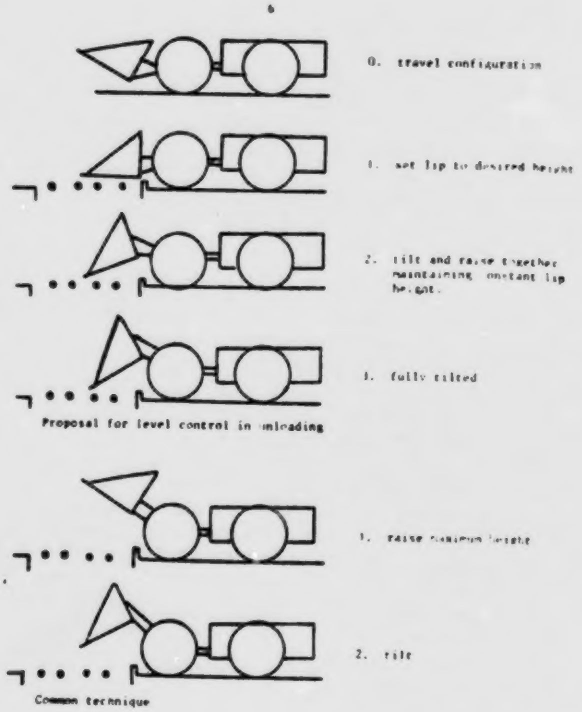

0. travel configuration
1. set lip to desired height
2. tilt and raise together maintaining constant lip height.
3. fully tilted
Proposal for level control in unloading
1. raise maximum height
2. tilt
Common technique

FIGURE 2. Improved unloading technique for scooptrams

A second means of minimizing the dispersion of dust from dump point would be by placing them in areas of low air velocities rather than in high air velocities as in main airways. At one site a dump point increased the dust concentration in a 125 m^3/sec airstream by one quarter of the permitted dust level.

If the dump points are connected to orepasses with other openings the falling materials can, and usually does, pump large quantities of very dusty air out into the workings. Elaborate interconnection and exhaust systems are required to control air concentrations at dump points on multi-level ore and waste passes (2,3). Even with them the dust leakage can be relatively high and decreases in dust exposure to all the workers on the level would be obtained by siting them close to the return airways, rather than close to the intake as shown in Fig. 3 or by using exhaust systems to draw off the dusty air at each dump point.

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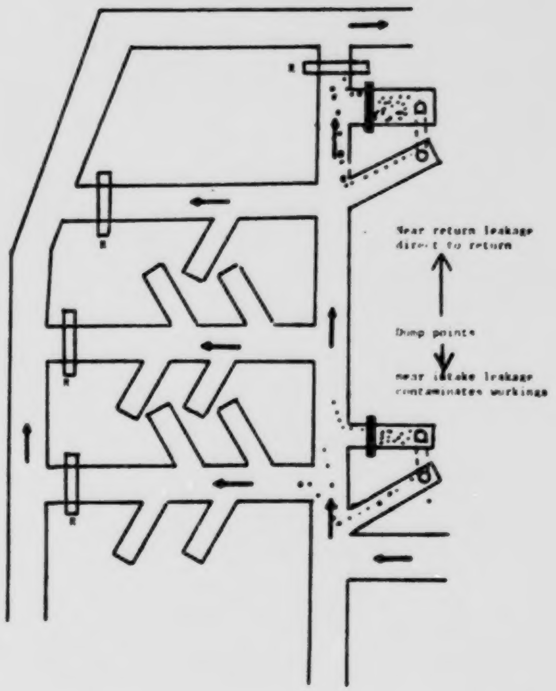
Near return leakage direct to return
Dump points
near intake leakage contaminates workings
R
R
R
R

FIGURE 3. Effect of dump point site on dust leakage into workings

3.21

Section 3 - Chapter 21

How Air Quality can be Monitored in an Underground Uranium Mine.

by

J. Bigu, M. Gangal and G. Knight

Canadian Mining Journal 104(3) 34-37 (1983)

SURVEILLANCE DE LA QUALITÉ DE L'AIR DANS UNE MINE SOUTERRAINE D'URANIUM

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L'exploitation des minerais d'uranium dans les mines souterraines libère et produit une grande variété de substances qui passent rapidement en suspension dans l'air et qui posent un danger pour la santé des travailleurs. Les substances sont soit libérées, ou leur taux de libération "normal" en l'absence d'activité minière est augmenté, à la suite de certaines activités minières, notamment le tirage, le forage et le chargement, soit produites en raison de l'utilisation d'outils, d'objets fabriqués et de machinerie dans les activités minières. La présente communication traite de mesures parallèles relatives au rayonnement, à la poussière et aux variables météorologiques au cours de plusieurs opérations minières dans une mine souterraine canadienne. Des mesures ont été effectuées dans trois mines d'uranium sur une période totale de plusieurs semaines.

How air quality can be monitored in an underground uranium mine

By J. BIGU, M. GANGAL and G. KNIGHT
Elliot Lake Laboratory, Canmet

The mining of uranium ores in underground uranium mines releases and produces a great variety of substances which readily become airborne, posing a potential health hazard to occupational workers. The substances are either released, or their "normal" rate of release, when no mining activity is present, is increased as a consequence of certain mining operations, including blasting, drilling, and mucking, or produced as a result of the use of tools, artifacts, and machinery utilized in mining operations. This paper reports on parallel measurements of radiation, dust and meteorological variables during several mining operations in a Canadian underground mine. Measurements were conducted at three uranium mines for a combined period of several weeks.

Experimental data pertaining to some radiation variables of interest were compared with theoretical data calculated using several mine models and a one-dimensional diffusion equation for the emanation of radon and thoron from mine walls. The mine models used here include the isolated mine model, the mine tunnel model and a mine model consisting of the mixing of "young" and "old" air. The isolated mine system is defined as one in which a certain quantity of radon gas is added initially to pure air and then decays, there being no replenishment or removal of activity from the system. In the mine tunnel model a source of radon is released at one point in the mine and then carried along with the ventilation air through the rest of the mine. The radon gas is constantly replenished by diffusion from the walls of the mine.

Measurements were conducted of radon and thoron gas and their progenies. Measurements of radon gas levels were conducted using a radon gas continuous monitoring system developed by EDA Instruments Inc, a firm based in Toronto.

Measurements were carried out to estimate the radon and thoron daughter levels. The Thomas (a modified, optimized version of the Tsivoglou) and Kusnetz methods were used to determine the radon daughter working level, WL(Rn). The Thomas method also permitted the estimation of the radon daughter concentrations and their state of disequilibrium.

In addition, the WL(Rn) was also determined by means of an MDA Model 811 instant working level meter (IWLM) manufactured by MDA, a firm based in the US. This instrument enabled determination of the WL in 3.5 min including sampling.

A second determination of the WL with the same sample, i.e. filter, is also possible by applying a correction factor to the readings obtained in order to account for radioactive decay. It is claimed that the second WL determination provides a good check on the first determination, and is also less sensitive to the "age of air", i.e. disequilibrium state of RaA, RaB and RaC'. The thoron daughter working level, WL(Tn), and the concentration of ThB were determined by a total gross α-count similar to the Kusnetz technique.

In order to correlate radiation and dust data with underground meteorological conditions, measurements were carried out for airflow (Q), temperature (T), barometric pressure (P), relative humidity (RH) and moisture content (MC). Airflow was calculated by the traverse method using an AM 5000 digital anemometer, manufactured by Air Flow Developments Ltd. Barometric pressure was measured with a precision aneroid barometer, type M2136, manufactured by Negretti and Zambra (Aviation) Ltd (UK). Temperature and relative humidity were measured with a sling psychrometer.

Measurements of aerosol concentration above $0.0013\mu m$ but below $1\mu m$ were carried out by means of a condensation nucleus counter type CN manufactured by Gardner Associates Inc, US. Aerosol concentration measurements were aimed at studying its relationship to α-particle concentration and also to unatta radon daughter products.

Table 1. Average values for radon and thoron WLs and ThB concentrations

Location	Average [ThB] pCI/L	Average WL(Rn) Corr	Average WL(Tn)	Average Total WL	Average WL(Tn)/ WL(Rn)	Remarks
Stope 254	0.94	0.084	0.116	0.2	1.38	Active
Stope 256	1.16	0.095	0.143	0.24	1.50	Inactive
Stope 255	1.06	0.107	0.131	0.24	1.22	Partly active
Intake	0.59	0.047	0.072	0.12	1.53	—

Two types of dust samplers have used. First, the Simquads version o Campeds dust sampler was usec measure the respirable dust. And sec a set of size selective samplers devel for the laboratory rock breakage st was used for measuring size dist tions.

The Simquads sampler was use pairs at the three radon gas sampler and at a fourth site chosen for intere dust studies. The set of size selec samplers was used in the air leaving operation being studied.

Dust production from an operation been obtained by subtracting the du the air entering from that in the air lea the operation and is expressed as dus unit of operation, e.g. mg/m drilled. During the experimental work the st 254, 255 and 256 were active, partly a and inactive, respectively.

In order to facilitate further readir description is given below of the mea of symbols and abbreviations not defined in the text. The subscript "C stands for measurements that have corrected for the presence of thoron d products. The subscripts Th and K st

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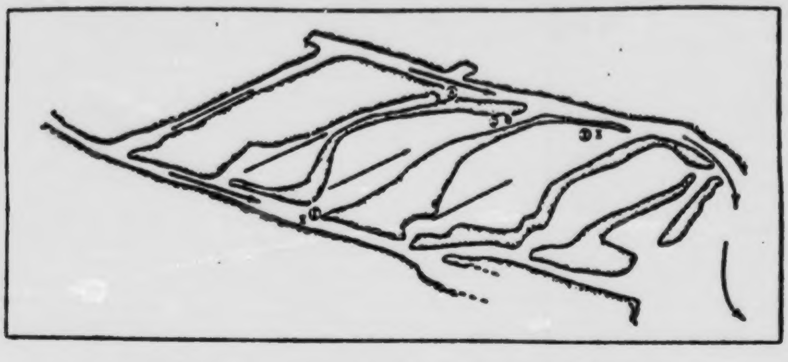
This article is an abridgement of the research re entitled "Studies of radiation, ventilation and dust underground uranium mine in the Elliot Lake are the same authors.

respectively, for measurements conducted by the Thomas and Kusnetz methods. The square brackets are used to indicate the concentration of the decay product, inside the brackets, in air. $WL(MDA)_1$ and $WL(MDA)_2$ stand, respectively, for the WL as determined by the MDA811 IWLM in the first and second reading.

Radon gas concentrations are related to mining operations and underground meteorlogical conditions. Large increases in the radon gas levels were observed as a result of blasting. An approximate four-fold and 3.5-fold increase in the radon gas activity was observed from Jan 26 and Jan 30 blasts. The above figures are in reasonable agreement with the rock tonnage obtained as a result of the blasts, i.e. 230 tons on Jan 26 and 200 tons on Jan 30. In principle, the amount of radon gas released in the blast can be approximately calculated and related to the rock tonnage by integrating the radon gas profile shortly before the upswing and after the downswing, and subtracting the 'background' contribution from this within the same limits, i.e. contribution with no blast. It can be seen that the radon level does not reach a steady, lower level until some time after the blast. This is to be expected as the gas is not suddenly released. However, some of this higher level is simply due to contamination of the cell under unusually high concentration levels.

The dependence of the radon gas concentration on underground barometric pressure could not be studied in detail as other environmental variables such as air quantity did not remain constant throughout the underground testing. However, and notwithstanding the above difficulties, indications were that the radon gas levels were not greatly, or clearly, affected by underground barometric pressure changes of up to approximately 8 mbar. Measurements carried out by other authors in sandstone uranium mines show an inverse dependence between radon gas concentration and barometric pressure. Our failure to detect this pressure dependence under our environmental conditions might be partly ascribed to the very low porosity of the mine rock hosting the uranium ore. Other environmental factors as well as relatively large fluctuations of the radon gas levels over short periods of time are suspected to be additional contributing factors.



Radon and thoron progenies

For the 254 raise there is a fair correspondence between the WL(Rn) and WL(Tn) daily profiles. This is to be expected provided the mine ventilation characteristics, other underground environmental factors and mining operations remain relatively constant. The ratio WL(Tn)/WL(Rn) is substantially altered by changes in air flow rate and flow characteristics decreasing with decreasing flow rate in a non-linear fashion, (see Fig. 2).

The unusually higher than normal values for WL(Tn) also occur at two other places where measurements were conducted, namely an inactive stope and at the intake.

The values obtained on Jan 30 day shift cannot be satisfactorily explained on the basis of barometric pressure and/or air flow changes. The only unusual environmental condition for that day was the higher relative humidity combined with low temperature. The most likely explanation for the observed results in sporadic disturbances of the ventilation, affecting the sampling area caused, for example, by opening and closing ventilation doors, or moving vehicles and men.

Fig. 1. Mine layout where experiments were conducted. Exact locations are indicated with crosses. The letters I, A and B stand for intake, Stope 254 and Stope 256, respectively. Position D is a dust sampling station, and it also stands for Stope 255

Inspection of the [Rn] and WL(Rn) daily profiles for the 254 raise do not indicate any clear-cut correspondence between these two variables as would, in general, be expected. However, a closer look at the data seems to indicate that if the time axes in the [Rn] profiles were divided into time segments and [Rn] average values for each segment were taken, the new "averaged" [Rn] profiles so obtained would roughly correspond to the WL(Rn) profiles. Confirmation of this assumption needs, however, further verification by resorting to time correlation, averaging and smoothing computer techniques.

No firm conclusions can be reached on the interrelationships between [Rn], WL(Rn) and WL(Tn) for the stopes where measurements were carried out. In general, however, mine air radiation levels (e.g. WLs) in active stopes varied with mining operations, increasing with the onset of some unit operations, provided environmental variables re constant during the measurements.

As expected, the numerical value the corrected radon daughter conce tions were lower than those corresp ing to the uncorrected values. Calcul shows that the uncorrected average v for [RaA], [RaB] and [RaC] are app mately 3.9, 29 and 19 per cent hi respectively, than the corrected av values. Moreover, the ratios [RaB]/[and [RaC]/[RaA] are, respectively, h than $[RaB]_{corr}/[RaA]_{corr}$ and [RaC $[RaA]_{corr}$ by 23 and 12 per cent. Av values of [RaA], [RaB] and [RaC Stope 254 were 24.7 pCi/L, 9.7 pCi/ 5.2 pCi/L, respectively.

Figure 3 shows that the experim ratios $[RaB]_{corr}/[RaA]_{corr}$ and [RaC $[RaA]_{corr}$ fall within the theor boundary lines (solid and broken expected for the above ratios as calcu for the three mine models. The age for data points lying on curve Y ca easily estimated, if one assumes tha mine-tunnel model holds and r daughter plate-out effects are ignore means of curve Y of Fig. 3, wher theoretical ages of air, in minutes indicated. For points outside curv lying between curves Y and Z, the a air cannot be so easily determined can be argued that they lie outside cu because of plate-out effects that RaA, RaB, RaC and RaC' different that the air representing these p consists of a mixture of air of diff ages or both.

The results of Table I indicate there is no dramatic difference bet the values for WL(Rn), WL WL(Tn)/WL(Rn) and [ThB] for active Stope 254 (mainly drilling), a active Stope 255 (occasional slus and an inactive Stope 256. The valu the above radiation variables at the ir were about half of those measure Stopes 254, 255 and 256.

The experimental ratios WL(WL(Tn) can be compared with exp theoretical values if the following ables are known: percentages of U_3O ThO_2 in the ore; porosity of the ore; meteorological variables undergrou

Theoretical values for the WL(Rn)/WL(Tn) can be calculat means of pertinent diffusion equa for radon and thoron gas in the ore. be shown that the concentration of g a given medium at a distance z fr source, i.e. C(z), is given by:

$$C(z) = \frac{\phi}{\lambda} e^{-z\sqrt{\epsilon\lambda/D}}$$

where, ϕ is the radon or thoron pr tion rate (i.e. number of gas a produced per unit time per unit volu interstitial space), ϵ is the ore porosit

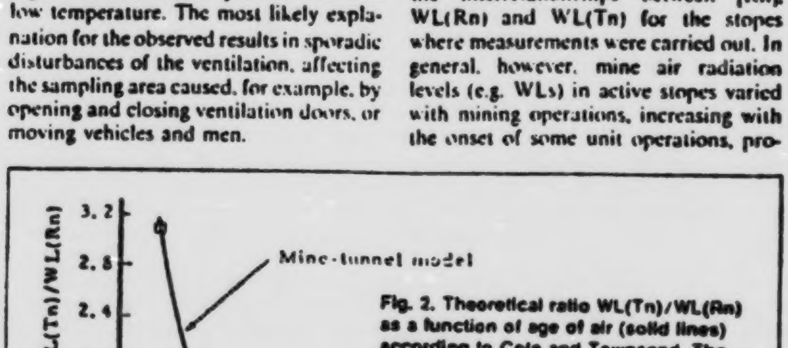


Fig. 2. Theoretical ratio WL(Tn)/WL(Rn) as a function of age of air (solid lines) according to Cole and Townsend. The cross-hatched area represents the range of experimental values for the ratio WL (Tn)/WL (Rn)

ratio of void to bulk volume). λ is the radioactive constant of the gas and D is the diffusion coefficient of the gas in the ore. ϕ/λ represents the concentration of gas at $z = 0$. Other diffusion equations similar to the one given above can also be used.

Applying the equation to radon and thoron gas the ratio $C(z)_{Rn}/C(z)_{Tn}$ can be built from which the number of atoms of Rn-222 and Rn-220 escaping the mine walls can be calculated. This ratio, in turn, enables the calculation of the ratio WL(Rn)/WL(Tn) as a function of the age of air. The gram ratio U-238/Th-232 in Elliot Lake mines varies widely from 0.1 to 4.0 depending on location. Taking an average gram ratio of 1:1 Cote and Townsend calculated the theoretical ratio WL(Rn)/WL(Tn) as a function of the age of air for the mine tunnel model and the isolated system. The results have been plotted and are shown in Fig. 2. The experimental average values for the ratio WL(Tn)/WL(Rn) for Stopes 254, 255 and 256 are shown in Fig. 2 for the estimated approximate average age of air calculated from Fig. 3. It can be seen that the agreement between theoretical and experimental values is reasonably fair.

The dust concentrations measured together with some ancillary data indicate that in many cases the amount of dust collected during one shift is too small to assess accurately by the gravimetric or x-ray diffraction techniques.

The normalized size distribution measurements indicate that there are some errors present and that smoothing could be used to improve the results. The major conclusions to be drawn from these measurements are: first the quartz dust is relatively coarser than the total dust; and second, a large proportion of the non-mineral dust is finer than 1μm.

The dust productions that could be estimated from this study are limited by the accuracy of total air flow measurements and by errors in estimating low dust concentrations.

Alpha activity collected in the filters of the size selector, i.e. horizontal elutriator, was measured. Due to the short lives of the radon daughter products of interest, long sampling times (up to a few hours), and long waiting times between end of sampling and activity counting, only α-activity due to ThC could be measured. The activity, given in terms of cpm/μg of collected dust, i.e. cpm μg^{-1}, is referred to here as the specific "attached" radioactivity (SAR). The SAR determined for the different top size cuts of the size selector (i.e. 1 to 10 μm) varied approximately from 0.3 to 1 cpm μg^{-1} for a normal shift and from 0.038 to 0.26 cpm μg^{-1} for a blasting operation, essentially indicating the significantly higher amount of dust collected in the filters. (Calculation of the SAR as a function of dust size range is rather complex because of the difficulty in accurately determining low dust levels from experimental data.) These results and other data gathered during the present and other experiments indicate that very little α-activity is associated with particulates in the respirable size range. As the attachment of decay products under our environmental conditions was rather high (>95 per cent), the α-activity was mostly due to decay products attached to aerosols of size below 0.5 μm.

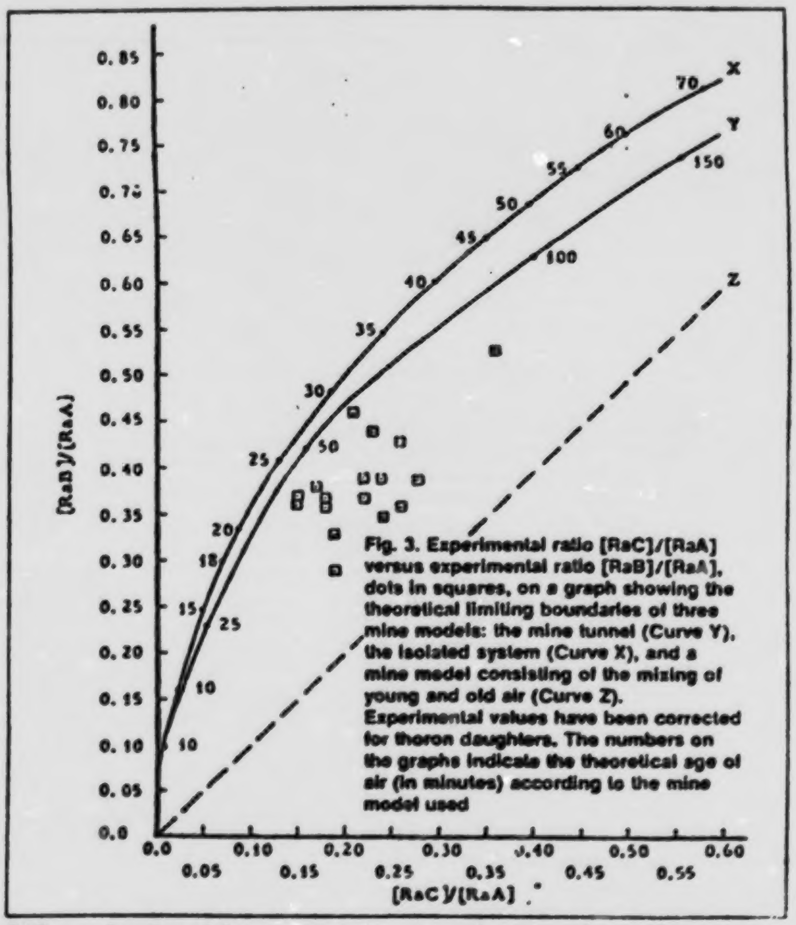


Fig. 3. Experimental ratio [RaC]/[RaA] versus experimental ratio [RaB]/[RaA], dots in squares, on a graph showing the theoretical limiting boundaries of three mine models: the mine tunnel (Curve Y), the isolated system (Curve X), and a mine model consisting of the mixing of young and old air (Curve Z). Experimental values have been corrected for thoron daughters. The numbers on the graphs indicate the theoretical age of air (in minutes) according to the mine model used

The data presented here show that for our experimental conditions, the agreement between the WLs as calculated by the Thomas and Kusnetz methods is fairly good. In the presence of thoron progeny both methods overestimate the WL(Rn) by about 20 per cent. The radon progeny state of disequilibrium has been found to agree well with theory. WL(Tn) was found to be higher than WL(Rn) by about 20 to 40 per cent. The ratio WL(Rn)/WL(Tn) was also found to agree reasonably well with approximate theoretical estimates calculated from diffusion theory and crude estimates for the ratio U-238/Th-232. The average ThB found was about 1.0 pCi/L. Areas where no work was conducted showed correspondingly lower values for the above variables. A direct relationship was found between $WL(Rn)K_{c_m}$ and WL(Tn).

The WLs as determined from measurements using the MDAIWLM Model 811 did not agree well with those obtained by the Thomas or Kusnetz methods, an experimental fact which is partly attributed to the presence of thoron daughters in mine air. Caution should, therefore, be exercised in the interpretation of experimental data obtained with the instrument when sampling in atmospheres containing thoron decay products.

Underground barometric pressure changes did not seem to affect radon gas levels, a fact that can be partly attributed to the low porosity of the rock. Reasonable correlation was found between radon daughter working levels and radon gas levels. Apart from blasting, no obvious correlation between respirable dust concentrations and radiation levels could be observed, although good correlation of the former and air quantity was found. The dust production from a blast was found to be higher than that from a full shift or any other operation in the mining area, showing the importance of blasting between shifts. ◆

3.22

Section 3 - Chapter 22

Generation and Control of Airborne Dust

by

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in Mine Ventilation. edited by P. Mousset-Jones

pp 139-150 A. A. Balkema Boston (1986)

Sources de poussières en suspension dans l'air des mines et réduction de leur quantité

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RÉSUMÉ : Une étude a été entreprise en vue de déterminer les principales sources de poussières en suspension dans l'air des mines et d'examiner les méthodes destinées à réduire leur quantité. Les expériences ont permis d'identifier trois types de poussières en suspension dans l'air et leurs sources : poussière minérale produite par toutes les opérations minières, bruines d'huile provenant de l'huile de graissage utilisée dans les machines à air comprimé, et particules provenant des échappements des diésels. On a étudié la fragmentation de la roche et la dispersion des poussières, et les résultats ont montré que la quantité de poussière produite dépend directement de la quantité totale de roche fragmentée et que la dispersion augmente avec le degré de manutention, l'énergie consommée pour produire une nouvelle fragmentation, l'énergie cinétique de la roche même, et la vitesse et la turbulence de l'air.

Deux méthodes importantes de réduction de la quantité de poussière sont le mouillage et la ventilation. L'efficacité du mouillage dépend du temps de mouillage, des propriétés de surface de la roche, du type d'agent de mouillage, de l'utilisation de vapeur et du degré de mélange mécanique; les appareils d'arrosage sont inefficaces pour éliminer les poussières fines qui sont déjà en suspension dans l'air. La réduction de la quantité de poussière par ventilation s'effectue en ajoutant de l'air afin de réduire la concentration des poussières, en évacuant ou en aspirant l'air chargé de poussière (de la zone où sont les travailleurs), et en réglant le sens d'écoulement de l'air.

On présente les résultats de mesures gravimétriques sur les poussières effectuées dans six mines pendant des opérations de tirage, de chargement, de transport et de roulage de la roche, et de forage, de même que pendant des opérations auxiliaires. Le tirage, le concassage et le transport dans les cheminées à minerai verticales sont les opérations qui ont produit le plus de poussière. Dans les zones d'exploitation, c'est la manutention du minerai plutôt que le forage qui est la principale source de poussières.

Deux séries d'expériences ont été réalisées en vue d'étudier l'effet de l'eau sur la réduction de la quantité de poussière dans les opérations de chargement des chargeuses-déchargeuses. Les opérations de broyage par voie humide ont produit des quantités importantes de poussière; les enceintes et l'extraction permettaient de réduire les exigences générales en matière de ventilation.

Des recommandations sont formulées relativement à la réduction de la quantité de poussière dans les mines en roche dure.

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Generation and control of mine airborne dust

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ABSTRACT: A study was undertaken to determine the major sources of airborne dust in mines and to investigate control methods. Experiments have identified three airborne dust types and their sources: mineral dust from all mining processes, oil mists from lubricating oil used in compressed air-powered machines, and particulates from diesel exhaust. Rock breaking and dust dispersion were studied and the results showed that the dust produced is directly dependent on the total breakage and that dispersion increases by the extent of the handling, the energy expended in creating new breakage, the kinetic energy of the rock itself, and the velocity and turbulence of the air.

Two main dust control methods are wetting and ventilation. The effectiveness of wetting depends on wetting time, rock surface properties, type of wetting agent, use of steam and on the extent of mechanical mixing; sprays are ineffective in removing fine dust that is already airborne. Controlling dust through ventilation is effected by adding air to dilute the dust concentration, exhausting or drawing dust-laden air (from the worker's zone), and by controlling airflow direction.

Gravimetric dust measurements from six mines are given for blasting, rock loading, transport and hauling, drilling, and ancillary operations. Blasting, crushing and vertical orepasses produced the most dust. In mining areas, ore handling rather than drilling was responsible for creating most of the dust.

Two sets of experiments were made to investigate the effect of water on dust control in LHD loading operations. Wet processes in milling operations produced substantial dust; enclosures and extraction could decrease general ventilation requirements.

Recommendations are given for dust control in hard rock mines.

1 INTRODUCTION

Dust has long been a major health hazard in the mining industry. There has even been evidence of silicosis in Stone Age flint workers.

This report forms part of a program to develop technology to solve problems related to underground mine workers' exposure to airborne, and thus, respirable, dust produced by various underground mining operations.

Studies were undertaken by the Mining Research Laboratories at Elliot Lake to determine the sources of fine, potentially airborne dust in mines and to develop control methods capable of reducing dust levels significantly below regulatory standards. Dust production measurements were taken with the CAMPEDS for gravimetric dust, respirable combustible dust, respirable mineral dust (ash), and respirable quartz dust (Knight 1978).

Rock breakage, dust dispersion and rock cutting processes are described as well as control methods by wetting and ventilation. Recommendations for improving dust control in hard rock mines are given.

The principles of dust generation and control are discussed in the following sections.

2 BREAKAGE

Dust is produced in all rock breaking processes except possibly when rock splits at a plane of weakness. In most processes examined the quantity of fine, potentially airborne dust was related to the quantity of coarser dust produced, that is, to the total amount of rock broken into finer sizes. Figure 1 shows the mean value and range of sizes of broken material produced from 1 cm lumps in a rotary crusher. This

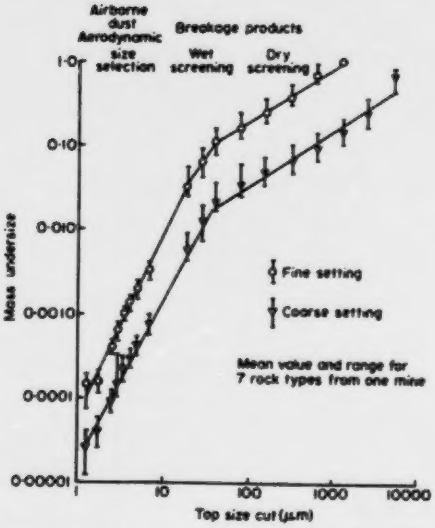

Fig. 1. Size distribution of breakage products and airborne dust in laboratory test.

Table 1. Estimated potential airborne dust from breaking massive rock to various sizes.

Maximum size of broken rock (metres)	Potential airborne dust in respirable size range (1) (g/t)
1	19
0.75	23
0.5	31
0.25	50
0.1	105
0.05	290
0.01 (1/2 in.)	600

information is important in evaluating the quartz content of airborne dust.

Discontinuities may occur in rocks with a marked grain size (Hamilton, 1957); These are most often found in sedimentary rocks with strong grains in a weak matrix. Despite this, the fact is that the amount of potentially airborne dust is directly dependent on the total breakage. Generally, breakage is directly proportional to the energy input and inversely to the rock strength. Table 1 shows the estimated quantity of potentially airborne dust in the respirable size range when rock is broken to various maximum sizes for transport assuming a uniform breakage procedure. Table 1 shows that a large increase occurs when the ore is broken into finer sizes.

3 DUST DISPERSION

Generally, only a proportion of the potentially airborne dust is dispersed. Therefore, it is expected that in breaking dry material, the dust generation and dispersion will resemble that shown in fig. 2. In a simple shatter test where 50 mm lumps were dropped 2 m onto a steel plate in a gentle airstream, less than 10% of the dust from a weak coal was dispersed compared with most of the dust from a strong coal (Hamilton 1957; Hamilton et al. 1963). Presumably the stress relief from the stronger coal imparted more energy or speed to the broken products leading to dispersion of a higher proportion of the dust. Test results suggest that dust dispersion was directly proportional to the energy input and independent of coal strength. In contrast, potentially airborne dust increased with decreasing coal strength.

It can be surmised that dust dispersed in handling processes increases with:

1. the amount of fine dust created in the breaking process
2. the extent to which the material is stirred up during handling
3. the energy expended to create new breakage
4. the kinetic energy imparted to the

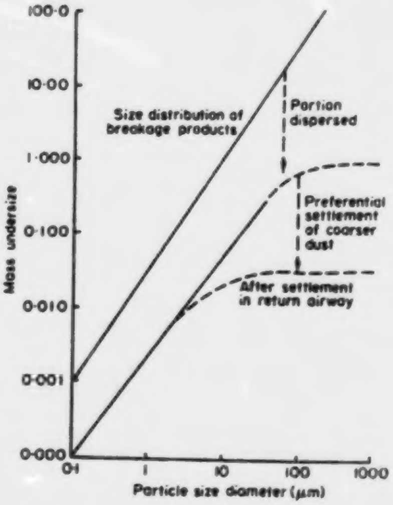

Fig. 2 Development of the size distribution of airborne dust.

freshly broken particles by the stress relief in the material broken

5. higher air velocities.

4 ROCK CUTTING PROCESSES

Rock cutting processes are used in coal mining machines, rotary drills, percussion drills, etc. Cutting is a misnomer; the characteristic of these machines is that they separate chips of rock from the main mass. The actual mechanics of raising a chip from the solid is complex, involving impact, fracture propagation, etc. Generally, two processes must be considered; cutting of the chip and its removal from the site.

For cutting the least amount of potentially airborne dust is produced when the chips are as large as possible. The design of cutting tools is complex, but minimum specific dust generation, i.e., dust generated per tonne, and minimum specific energy consumption are usually achieved together.

The problem of removing chips is most obvious in drilling where insufficient clearance or flushing agent may result in further breakage of the chips, binding and resultant loss of energy from the drill rod, decreased cutting speed, and increased specific dust generation and energy consumption.

5 DUST SUPPRESSION BY WETTING

Water is widely used in mines for dust control. Factors affecting dust suppression by wetting are:

1. Small potentially airborne dust particles can be attached to larger lumps and rendered non-dispersible by a thin film of liquid.

2. Water or other sprays are ineffective in removing respirable dust particles that are already airborne, unless very high accelerations are applied as in high pressure-drop wet scrubbers.

3. To be fully effective the liquid has to spread over the entire surface of the rock. The wettability of the rock depends on its surface properties and those of the liquid. Experiments have shown that most common rocks except sulphide minerals and coking coals are wettable.

4. It has been shown that it takes a long time for water to spread over the surface of a rock pile. Table 2 shows shatter test results for six coals after wetting and standing (Hamilton 1963).

5. Adding a wetting agent to water has been proposed. Laboratory experiments indicate improvement, which suggest that (Hamilton 1963):

a. wetting agents reduce spreading time

b. high concentration over 1% is required

c. the effect is most marked for difficult-to-wet rocks such as coking coals and sulphides

d. the use of wetting agents in sprays reduces the size of droplets which could also be achieved by increasing water pressure; no other measurable effect on the collection of airborne dust has been detected.

However, mine trials have failed to show any significant improvement in dust suppression. Wetting agents may only be of value in certain operations. It must also be noted that wetting agents may interfere with flotation processes used in ore preparation.

6. Obtaining a water layer by feeding steam into the rock pile is effective and decreases spreading time. Steam can be fed into moving rock in an enclosure at a transfer point on a conveyor belt.

7. Gentle mechanical mixing accelerates spreading of water over the rock surface. In laboratory tests two minutes of mixing in a low-speed tumble mill was sufficient for full control as shown in fig 3. Mechanical mixing may effectively improve dust suppression on conveyor belts and during drilling.

Table 2. Dust raised from various materials after treatment with water.

Material	Water Addition Level (mass %)	% Dust Dispersion			
		time of standing (min)			
		1	5	30	300
Coal coking (301)	10	93	87	79	70
Coal bituminous (902)	10	82	61	50	35
Coal bituminous (802/902)	10	-	50	32	20
Shale a	2.5	66	21	11	9
b	2.5	65	24	21	10
c	2.5	40	28	24	15

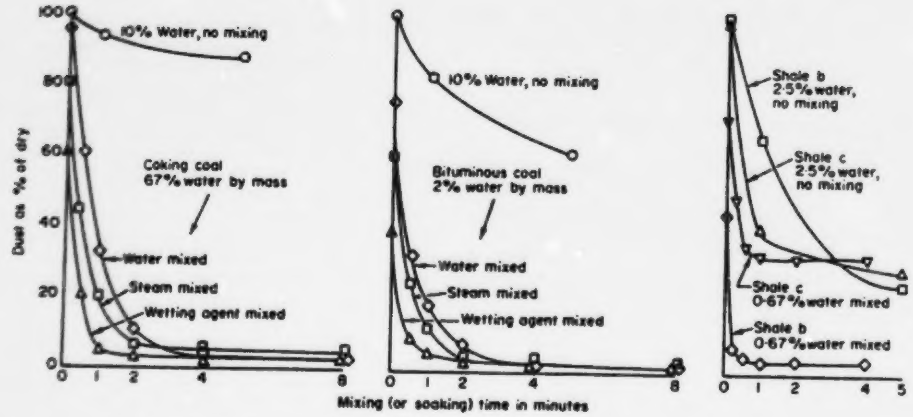

Fig. 3. The effect of mechanical mixing or soaking after the addition of water, steam and 2% wetting agent solution.

8. It has been shown in rock and coal cutting operations and drilling that water is most effective when applied as close to the cutting point as possible and that this can be achieved by feeding water through the tool bit and onto the cutting face.

9. Feeding water to machines has two major problems: 1) the human one of ensuring that the water supply is connected and turned on which can be avoided by interconnecting the water valves and the power supply and 2) clogging due to dirt and pipe scale for which it has been recommended that spray orifices have a diameter of not less than 1.5 mm and be protected by filter screens on or close to the machine.

10. Muck should be kept wet during handling and transport because of long wetting times required when dry.

11. Most liquids are effective dust suppressants. Oils and salt solutions have been used specifically to avoid drying or freezing. Drying of settled dust in underground roadways has been prevented by using hygroscopic salt as a binder.

12. Foam appears to show two main advantages, a barrier against airflows giving rise to dispersion and minimizing the quantity of liquid applied.

6 DUST CONTROL BY VENTILATION

Ventilation can control dust by: adding air to dilute the dispersed dust; exhausting or drawing dust-laden air away from the operation to prevent it from reaching workers, and controlling airflow direction.

It is usually assumed in dilution ventilation that an increase in airflow will lead to a corresponding reduction in dust concentration, i.e., doubling airflow will halve the dust concentration. However, this is not entirely true as the decrease in dust concentration is usually not as great as the increase in ventilation. It has been shown on English and German longwall coal faces that respirable dust concentration decreases with increased airflow at low velocities, reaches a minimum at 3 to 6 m/s and increases at higher velocities. Presumably increased air velocity tends to stir up the dust and disperse it, eventually off-setting the increased dilution.

Exhaust ventilation is effective when the dust source is enclosed and sufficient dust-laden air is drawn out to entrain the dust and prevent it from reaching the workers. For this, air must have sufficient velocity to pick up and retain the dust. A velocity of 1 m/s at the entrance to a hood is usually considered suitable for design purposes. However, higher values may be necessary if the ambient velocities exceed 0.5 m/s or if material moves out of the enclosure as on a conveyor belt. The exhausted air can be either passed directly to a return airway or filtered and returned to the ventilation circuit.

The quantity of air required for dust control of an enclosure with exhaust ventilation is decreased by:

1. reducing openings to a minimum

2. proper maintenance
3. lowering general air velocities
4. decreasing air turbulence from moving parts or from material entering and leaving
5. avoiding pumping effects, i.e., rotating or moving components acting as fans can push air out.

Exhaust ventilation generally requires much smaller volumes of air than dilution ventilation to control dust concentrations.

Airflow direction is mentioned in most manuals as a means of controlling dust but these generally do not emphasize its possibilities. Basically, it can have an intermediate effect between that of dilution and exhaust ventilation. In underground mining where airflow is necessarily controlled, dust exposure may be greatly reduced by ensuring that air from dusty operations passes directly to return airways and that most work is done on the intake side. For instance, stope drilling and mucking should be planned so that drillers are not exposed to dust from mucking and the mucking machine should be operated from the air intake side.

A two-fold difference in the dust exposure of two men working in a development heading was found in one study over four sampling days. Presumably this was due to one man preferring to work in the stream of high velocity fresh air coming from the duct whereas the other did not.

Diffuser nozzles have been used on high speed ventilation ducts to supply a comfortable stream of clean low-velocity air to workers.

7 DUST MEASUREMENTS IN MINES

For discussion purposes, hard rock mining consists of:

1. separating ore from surrounding rock and breaking it into pieces small enough to transport
2. loading
3. transporting and handling
4. drilling
5. ancillary operations

7.1 Dust Measurement Technique

"Dust production" is the term most descriptive of dust generation and dispersion into the air at a mining operation. Dust was measured with the CAMPEDS gravimetric dust sampling system (Knight 1978). Samples were collected on silver membranes and were weighed three times to give tare mass, gross mass and mass after ashing. They were further analyzed by X-ray diffruction for mass of quartz. These measurements gave four assessments:

1. total respirable dust
2. respirable combustible dust (defined as loss in mass on ashing at 500°C),
3. respirable mineral dust (ash),
4. respirable quartz dust.

Possible minor damage to the filter when loading and unloading the sampler can lead to large errors in estimating the mass of total respirable dust. This occurred particularly on the light samples in most of these studies and frequently caused difficulties in estimating the respirable mineral dust, which should equal total minus combustible, and the percentage of quartz in the dust. Note however, that the quartz measurement is absolute and is an order of magnitude more sensitive and accurate than weighing.

To facilitate comparison between mines, estimates of respirable mineral dust production were made from the quartz measurements and from the average value of the quartz content in heavy ashed dust samples, as well as from the measured difference between tare and ashed masses.

Sampling stations were set up in the airways both upstream and downstream from each operation. The stations were chosen to give the most uniform mixture of dust and air possible. Replicate samplers were strategically placed to obtain best readings without obstructing passage for men and vehicles. The samplers were kept running after the operations stopped to allow time for the dust to pass the return station. Airflow measurements were made at the stations and a recording anemometer was used to observe changes in airflow and to assist in estimating the total air volume passing each station.

Total dust produced at each operation was determined by multiplying the dust concentration at each station by the total corresponding airflow and subtracting the resultant figures at the intakes from those at the returns. This figure was then divided by the unit of production - tonnes of ore, length of hole drilled, or other unit as applicable - to give specific values per unit of production.

7.2 DUST PRODUCTION MEASUREMENTS

The measurements taken in six mines are summarized below.

Blasting

Measurements were made on airborne dust

Table 3. Blasting.

Site	Airflow (m^3/s)	Tonnes	Sampling Period (min)	Number of Tests	Respirable Dust Production (mg/t)			
					Total	Combustible	Mineral	Quartz
Total mine	450	2900	210	1	1200	540	450	300
Steep stope	2.5	180	330	1	2100	600	1400	700
Flat heading	20	270	360	1	1800	1400	300	150
Secondary (6 oversize rocks)	7	6	30	1	909	-	700	70
Mean					1500	900	750	-

reaching surface after production blasting between shifts and underground after blasting in a stope and heading, and after secondary blasting in a drawpoint (Table 3).

It is difficult to measure dust produced in a blast because of disturbance to the airflow. Future studies should determine the energy input from the explosives in at least a semi-quantitative form.

Clearly, blasting in hard rock mines produces large quantities of dust, emphasizing the importance of evacuating men and allowing adequate time for ventilation to remove dust and fumes.

Loading

The following equipment was used to load broken rock for transport (Table 4):

1. rail-mounted compressed air-powered mucker emptying into a rail car in development headings
2. electric and compressed air-powered slusher operating in drifts and stopes (2a,b,c)
3. diesel-powered load-haul-dump machines (LHD) of various sizes operating in headings and drawpoints (3a,b). In some cases LHD's loaded the rock into diesel-powered trucks. A separate measurement of dust produced in this transfer was not possible because the layout of the heading and the ventilation system prevented selecting sampling stations with adequate mixing of dust with air.

It can be seen that rock loading produces substantial mineral dust. The electric-powered slushers produced negligible combustible dust. The compressed air-powered equipment produced measurable quantities, presumably of lubricating oil mist. The diesel-powered equipment produced large quantities of combustible dust.

The quantities of mineral dust varied substantially from one site to another for which a number of factors were responsible:

1. Wetness of rock - although water was always used, apparently not all of the rock surfaces were wetted.
2. Roughness of floor - it was apparent that loading was more difficult and presumably more dust was produced on rough floors than on smooth.
3. Clean up and scaling - loading machines used for clean up at two sites produced much more dust per tonne of muck than normal loading operations.
4. Operator finesse - some drivers, especially on lower-powered machines, developed techniques for rapid loading, presumably with low energy input and low dust production.

Rock Transport and Handling

After loading, rock is transported horizontally and vertically for considerable distances to surface, usually via an underground crusher. A limited number of such operations were examined (Table 5):

1. Filling rail cars from a chute with a free fall of 1 to 2 m.
2. Dumping rock onto a grizzly from diesel-powered LHD's and trucks. This operation included breaking oversize pieces with a hydraulic pick. The measured dust was not the total produced but only that part escaping the local system below the grizzly and from the filter system.
3. Near vertical ore and waste passes.

a. This system had dump points at every 35 m vertically with interconnections between ore and waste passes at each level; an exhaust system drew dusty air from the lowest level.

b. The part of this system examined consisted of a 30 m section of orepass with fingers at top and bottom; the free fall of material induced airflow out through the lower finger.

c. The system consisted of a 600 m vertical orepass with dump points at the top and at 120 m intervals; dust leakage from the top was calculated on tonnage from this level and at the second level on tonnage from both upper levels.

4. Underground crushers; although total dust was measured on systems a and b, only that leading from the crusher and air exhaust system with filter was measured on c and d; at two other crushers, dust leakage could not be estimated because of low ventilation rates.

5. Big rock handling; rocks too large for the crusher were handled at this mine by a crane and dropped into a side heading for secondary blasting.

6. Skip-loading; one skip-loading

Table 4. Loading of rock.

Site	Operation	Airflow (m³/m)	Tonnes	Sampling Period (min)	Number of Tests	Respirable Dust Production (mg/t)			
						Total	Combustible	Mineral	Quartz
1	Mucker in heading								
	Range	1.5-3	60-90	210-330	3	40-200	12-180	14-42	7-21
2a	Slusher in raise								
	Range		30-50	69-150	3	0-50	0-6	8-80	4-19
2b	Slusher in stopes								
	Range	0.6-4	50-200	220-280	4	11-150	0-10	40-170	20-84
	Range	.5-1.5	60-80	210-270	4	60-500	90-250	100-250	10-110
2c	Slusher in stope								
	Range	0.7-1.3	60-100	-	4	80-250	30-65	40-200	20-53
3a	LHD in heading								
	Range	0.6	500	-	1	136	43	100	23
	Range	10	200	100-180	9	225-980	240-450	100-400	29-315
3b	LHD in drawpoint								
	Range	3.5-8	250-500	90-345	4	200-650	170-280	50-200	16-39
	Range	1-17		100-350	5	260-3000	230-350	150-1300	15-130
Overall range of test means								26-540	
Overall mean								140	

Table 5. Ore handling.

Site	Operation	Airflow (m³/s)	Tonnes	Sampling Period (min)	Number of Tests	Fall (m)	Respirable Dust Production (mg/t)			
							Total	Combustible	Mineral	Quartz
1	Loading mine cars	3-73	140-420	30-116	2	3	35	15	70	8
2	Dumping on grizzly	70	800	300	1	1-3	270	-	54	27
3a	Orepasses	40	2000	320	1	300	700*	low	800*	400
b	Orepasses	1	200	120	1	30	105	7	70	16
c	Orepasses									
	top level, mean	40	600	200	3	300	270	90	180	18
	182 m down, mean	25	1600	140	7	300	250	80	160	16
4a	Underground crusher	3	2400	325	2	3	600	20	800	400
b	Underground crusher	3	800	200	1		200		250	130
c	Underground crusher	2.5	200	120	1	3	100		60	15
d	Underground crusher	3	750	390	1	3	150		90	22
5	Big rock	3	20	390	1	3	110		35	10
6	Skip loading	5	514	210	1	6	115	15	30	16

*Lower total than mineral assessment is an indication of the weighing errors.

Table 6. Drilling.

Site	Operation	Airflow (m³/s)	Metres	Sampling Period (min)	Number of Tests	Respirable Dust Production (mg/m)			
						Total	Combustible	Mineral	Quartz
1	Jackleg mean	2	105	226		9	8	1.2	0.6
	Mean	6	85	200		2.4	0.6	0.6	0.3
2	Bar-arm mean	1.5	180	153	2	29	15	3	0.6
3	Jumbo mean	1.7	300	300	2	4.5	3	1.5	0.3
	Mean	10	180	225		20	18	1.8	1
4	Mini borer				2	85	6	3.5	1
						(8)*	(0.6)*	(0.35)*	(0.1)*
5	Down the hole range		46-120		4	120-1000	60-700	60-350	16-110
						(90)*	(70)*	(20)*	(10)*

*Values in brackets are those for equivalent length, by rock volume removed, in 50-mm diameter hole.

facility fed from an orepass was examined.

Most ore handling operations produce large quantities of dust and many achieve partial or complete dust control using exhaust air systems.

Drilling

Drilling is a major operation in most hard rock mines and uses a substantial proportion of the total manhours. Before the advent of wet drilling it was considered the most hazardous occupation leading to silicosis.

Five drilling systems were studied as shown in Table 6. Dust production is given as mg/m of drillhole.

1. Jackleg compressed air-powered rotary percussive drills; these data could not be separated from drilling for roof bolts using a stoper; dust production is given in terms of total length of hole; bit diameter was about 40 mm.

2. Bar and arm compressed air-powered rotary percussive drills; these drilled long holes of about 50 mm in diameter.

3. Jumbo-mounted compressed air-powered rotary percussive drills; bit diameter was about 50 mm.

4. Mini-borer; rotary drill, drilling down-holes of about 150 mm in diameter.

5. Down-the-hole drills; four compressed air-powered rotary percussive drills were used in the same stope for which the total production was measured on four separate shifts; bit diameter was 110 mm.

Table 6 indicates that all drills except the down-the-hole were characterized by low dust production. This made it difficult to measure the increase in dust concentration between intake and return air except at low rates of airflow.

The down-the-hole drills produced copious quantities of airborne dust because compressed air was used as the flushing agent. Although some water was used it was apparent that dust control was less effective than with any other drill even allowing for the greater quantity of rock broken per metre of hole.

Ancillary Operations

A few ancillary operations were examined for which production results are given in Table 7:

Operations 4 to 8 in Table 7 were in a surface mill processing iron ore. Even though all the processes were wet, substantial quantities of dust were produced. Enclosures should be considered.

7.3 SUMMARY OF DUST PRODUCTION

In most mines examined gravimetric assessments show that rock handling and specifically loading are a a much greater hazard than the historically hazardous operation of drilling. Although partly due to the parameter change from number to mass for the finer dust in drilling compared with other operations, the main factor is the effective dust control achieved by feeding water to the bit. In most of the mines examined the major mineral dust exposure was due to loading. Secondary blasting in the mining area or substantial contamination of the intake air by the ore transport system was equally important in some mines.

Mine transport systems can produce large quantities of mineral dust but effective control has been achieved by entraining dust from non-mobile operations in an airstream and filtering or directing it to a return airway.

Table 8 shows the estimated dust production for the mine where most of the experimental work was undertaken. This mine operated at depths between 240 and 600 m using horizontal track drifts and stopes on the 2 to 6 m thick ore horizon with jackleg drills and electric slushers. The ore output was 2700 t/shift and production blasting as carried out between shifts.

It can be seen that most dust was produced in the ore transport outbye of the active mining area, where in this particular mine the orepasses are near the shaft and away from the extraction area. The main dust sources were well controlled by exhaust ventilation and only a small proportion of the transport dust leaked into the working areas and travelways. The production blast was the next major source and exposure was avoided by blasting between shifts.

The mineral dust production in the active mining areas is only about 5% of the mine total. Most of this arises from handling with only little from drilling.

An LHD operator's exposure was analyzed in a second mine which worked a near vertical orebody. The orepasses were placed close to the intake allowing dust contamination of most of the mining zone. The operator's exposure comprised:

a. 15% in the orepass heading;

b. 12% leakage from orepass into intake air; this also formed a major part of dust exposure for other miners on the level.

c. 10% loading muck;

d. 30% directly from engine exhaust.

7.4 DUST CONTROL EXPERIMENTS

Loading is one of the dustiest

operations to which miners are exposed. To date two sets of experiments were made to investigate the effect of water control on dust in LHD loading operations. In the first set carried out in a drawpoint in high sulphide ore, loading was carried out dry or with 1-, 2-, or 4-bar pattern sprays. In the second set, muck piles in headings six or more metres wide were examined using various wetting times with simple jets from hand-held or blocked-in-position hoses and nipples.

Results from the first set, based on differences between return and intake as well as between drawpoint and intake air samples, are given in Table 9.

It was clear that adding water decreased mineral dust production but not fully as dry muck was always visible immediately after loading.

Results from the second set of tests on highly siliceous rock muck piles are shown in Table 10. Sixteen tests were made on muck piles in various headings and represented normal mine operation. The last two tests were made on a similar muck pile at a site having through-ventilation. It was obvious that water additions could reduce dust levels to less than 20%. It was also evident during the first few buckets at the start of the shift that dry muck was frequently visible. The extra wetting tests in which loading of a muck pile was continued after the lunch break led to a further substantial reduction in mineral dust.

The two tests showed somewhat erratic results on combustible dust production. Although adding water could affect ease of loading and power requirements or even modify the soot production by the engine, it is believed that the erratic results are probably due to the errors in assessing dust, or to variation between engines.

7.5 COMPOSITION OF AIRBORNE DUST IN MINES

The experiments on dust production have identified three airborne particulate types and their sources:

1. mineral dust from all mining processes.
2. oil mists from lubricating oil used in compressed air-powered machines.
3. diesel exhaust particulates.

Mineral dusts are not all equally hazardous to health. Free silica minerals and mineral fibres (asbestos) are of an order of magnitude more hazardous than most other common minerals. Of the free silica minerals, quartz is the most common, and in this study was the only "more hazardous" mineral measured separately. In most mines tested the respirable quartz formed a constant proportion, within the limits of experimental error, of the respirable mineral dust. This proportion was always less than that in the rock mined. In one mine with a massive sulphide ore there was some evidence that the quartz content was higher in the airborne dust in the mining zone than in the crusher room. Presumably, by the time the rock reached the crusher the silicate components were well wetted and their dust was better controlled by the various water additions en route.

In jackleg drilling it was found that 90% of the dust collected on the filter was combustible. It was presumed but not proven that this was lubricating oil atomized by the high energy of the exhaust air. A simple calculation showed that the measured quantity of respirable combustible dust was about 0.33% of the amount of lubricating oil sent underground for use in drills.

The diesel exhaust particulates are a complex mixture of soot, unburnt hydrocarbons, and sulphuric acid. The sulphuric acid mist is produced by oxidation of some of the sulphur dioxide in the catalytic purifier, and may be absorbed onto the soot particles.

In this report only the total exhaust particulates as indicated by the respirable combustible dust, i.e., loss in mass on ashing, are considered.

Table 11 shows the composition of the dust produced at various operations and its probable source. In view of the limited number of operations examined, the extent of variation in composition is probably too low and the figures should be used only as an indication of the possible hazards.

8 RECOMMENDATIONS FOR DUST CONTROL IN HARD ROCK MINES

8.1 Blasting

Because of both dust and fumes, blasting should be carried out so that men are not exposed to contaminated air either in the area itself or to the air leaving it. Blasting techniques should aim at producing a minimum of fines and oversize lumps, and producing the smoothest floor possible (Hagan, 1979).

8.2 Rock handling

Rock breaking produces large quantities of

Table 7. Ancillary mining operations.

Site	Operation	Airflow (m³/s)	Tonnes	Sampling Period (min)	Number of Tests	Respirable Dust Production (mg/t)			
						Total	Combustible	Mineral	Quartz
1	Drill prep. (ST 5)	10		30	1	1800	1000	800	400
2	Hyd. backfilling	2.5	800	180	1	270	-	-	-
3	Conveyor belt[3]	4	4000	360	12	21	1	16	5
4	Autogenous mill	2	2000	360	2	65		27	9
5	Pebble mill	2.2	500	360	2	5		11	4
6	Magnetic separator	0.2	320	360	2	1		1	3
7	Flotation	0.2	320	360	2	3		2	7
8	Rolling drum	2.7	400	360	1	13		13	-

[1] Toe scraping ST 5. [3] Dry muck conveyor excluding feed point.

Table 8. Estimates of total dust produced for one mine shift.

Operation	Tonnes	Respirable Dust Production g/shift				Mineral Dust as % of	
		Total	Combustible	Mineral	Quartz	Entire Mine	Mining Area
Between shift main blast	2700	5600	2800	2600	1300	34	
Mining area							
Secondary blasting	100*	100	20	80	40	1	15
Slushing	2400	350	20	330	165	4	63
Mucking	400	40	30	10	5	0.1	2
Car loading	2700	115	60	56	27	0.7	10
Drilling	2700 (2200 m)	22	20	3	1.5	0.04	0.6
Scaling etc.**		10	-	10	5	0.1	2
Total		637	150	487	243	5	100
Outbye							
Rail transport	2700	65	60	5	2	0.1	
Dumping into orepasses**	2700	60	10	50	25	7	
Orepasses	2700	2700	60	2600	1300	34	
Underground crusher	2700	1800	-	1800	900	23	
Skip loading	2700	160	40	100	50	1.3	
Total		6800	170	4600	2300	60	
Entire underground mine		11000	3100	7700	3850	100	

*Estimates based on a guess as to variable secondary blasting carried out. **Estimate.

Table 9. Effect of water on LHD loading high sulphide ore.

Sprays		Respirable Dust production (mg/t)				Relative Respirable Dust Production (mg on filter/bucket)				Dust as % of Dry	
No.	Cond.	Total	Combustible	Mineral	Quartz	Total	Combustible	Mineral	Quartz	Combustible	Quartz
Mean	Dry	280	330	21	59	58	30	21	7	100	100
1	Sprays	18	50.15	47	20	30	20.67	8	3.5	60	42
2	Sprays	9	36.11	-11	16	9	4.13	5	0.9	12	20
4	Sprays	200	130.40	110	13	3	0	1.4	0.5	0	15

Table 10. Effect of water on LHD loading high silica ore.

Description	Runs	Tonne	Respirable Dust Production (mg/t)				Dust as % of Dry	
			Total	Combustible	Mineral	Quartz	Combustible	Quartz
Normal mine practice								
Range	9	152-424	225-1300	240-1100	59-639	29-315		
Mean		1800	700	525	150	75	105	25
Early start mean	2	160	825	675	185	92	135	31
Extra wetting range	5	32-200	600-1500	600-1500	28-96	14-48		
Mean	4	600	900	825	62	31	165	10
Dry test	1	120	900	500	600	300	100	100
Same pile after 1½ hours wetting	1	88	800	700	110	55	140	18

Table 11. Composition of airborne dust produced by various operations.

	Ash %	Mineral Dust Total %	Combustible Dust %
Blasting	88	50-70	12
Loading			
C.A. mucker	25	25	75*
C.A. scraper	70	70	30*
Electric slusher	95	95	5
Diesel LHD	20-40	20-40	60-80**
Drilling	10	10	90*
Orepasses	100	100	0
Crushing	100	100	0

*Lubricating oil mist.
**Diesel exhaust particulate.

airborne dust, and although the broken ore needs reducing further, additional breakage should be minimized at all sites where men may be exposed and confined to such areas as crushers where enclosures and filtration can capture most of the dust. In handling rock, attention should be given to:

1. Minimizing free fall as the amount of dust produced is proportional to the distance dropped.
2. Using slides as sliding a given vertical distance reduces dust production compared with falling freely.
3. Making floors as smooth as possible to minimize energy required to pick up or drag rock.
4. Locating and designing sites for secondary breakage of oversize rock such as grizzlies or dumps, so that the dust dispersion can be entrained and either directed to a return airway or collected by filtration; in particular, they should not be located in main airways where high air velocity increases dust dispersion.
5. Vertical orepasses. These are a major source of dust because of the piston effect of falling rock pumping air out of the orepass into the work place. Pressures can be developed high enough to lift 1 cm thick steel plate doors.

Although pressure can be reduced by interconnecting ore and waste passes at each level, there will still be some leakage of dusty air and elaborate precautions may be necessary to divert this away from the work areas. Siting orepasses close to the return airways may be well worthwhile.

The use of off-vertical orepasses could possibly decrease dust production by transforming free falling to a sliding motion, decreasing fresh breakage. A controlled feeder might prevent the formation of plugs and greatly decrease the pumping of dusty air.

6. Wetting broken rock. This can prevent fine dust from becoming airborne by binding it to large pieces of muck. To be effective a thin liquid layer must cover all free surfaces in the rock pile. For the liquid to spread over the rock its surface must be wettable. Silica rocks are usually readily wettable whereas some sulphide minerals are not. Even for silica rocks, wetting times of more than two hours are required to completely wet a muck pile and minimize dust dispersion during loading. For sulphide rocks wetting times may be much longer.

The quantity of water required however is not great - a few tens of litres per tonne and the use of mist sprays applying water at a low rate evenly over the top of the muck pile for hours is probably most effective. A hand-held hose jet is usually not satisfactory and encourages inadequate wetting.

The mechanical mixing involved in rock movement in orepasses and crusher operations spreads the water much faster and quickly traps any dust created by new breakage.

7. Some ventilation is essential to dilute the dust concentration. Whenever possible, airflow direction should be such that the air flows away from workers towards the dust source.
8. Enclosure of dust handling operations is effective in decreasing air velocity over moving rock and reduces the dispersion of dust.
9. Where breakage is unavoidable, such as in an orepass and crusher operations, enclosures and air extraction are almost always required for dust control.

8.3 Drilling

Normal wet drilling is not a substantial source of dust as the application of water close to the cutting edge and its virtual immersion in water in the hole prevents dust escape. However, large quantities of potentially respirable dust are formed so that dust control must be considered in any change in drilling technique, such as when going to down-the-hole drilling (Table 6).

LHD's, and probably other machines, when preparing faces for drilling, apply high forces and expend much energy, thereby causing fresh breakage and creating more potentially airborne dust. The LHD bucket is a poor tool for cleaning faces and alternatives are required.

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3.23

Section 3 - Chapter 23

Computer Predicted Airborne Respirable Dust Concentrations in Mine Air Recirculation Systems

by

S.G. Hardcastle

in Mine Ventilation. edited by P. Mousset-Jones

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Prévision informatisée des concentrations de poussière inhalable en suspension dans les systèmes de recirculation d'air dans les mines.

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RÉSUMÉ : On présente un historique des études et des essais pratiques portant sur la recirculation contrôlée à grande échelle dans les systèmes de ventilation des mines. On passe aussi en revue certaines études portant sur le transport et la filtration des poussières inhalables en suspension dans l'air des mines qui peuvent être pertinentes à un circuit de recirculation.

À l'aide d'une théorie généralisée sur les polluants dans un système de recirculation, on ajoute les effets de la sédimentation des poussières et de la filtration des poussières par différence granulométrique; cette théorie a servi à élaborer un modèle de simulation exécutable sur la plupart des micro-ordinateurs.

Le programme informatique demande peu de données en entrée. Des valeurs résultantes sont obtenues pour de vastes gammes de pourcentage de recirculation et d'efficacité de filtre. Le programme permet de prévoir : les variations des débits massiques et des concentrations des poussières en suspension dans l'air de retour et dans l'air réintroduit à l'entrée du système de ventilation.

Les résultats du modèle informatique sont ensuite présentés sous forme graphique. Ceux-ci démontrent les avantages possibles de la recirculation relativement aux poussières inhalables en suspension dans l'air.

Computer Predicted Airborne Respirable Dust Concentrations in Mine Air Recirculation Systems.

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ABSTRACT: A history is given of investigations into, and field trials of, large-scale controlled recirculation in mine ventilation systems. A review is also presented of selected transportation and filtration studies of airborne respirable mine dust that may be relevant in a recirculation circuit.

Using a generalized theory for pollutants in a recirculation system, the effects of dust sedimentation and size differential dust filtration are added; this theory has been converted into a computer simulation model executable on most micro-computers.

The computer program requires little input of data. Resultant values are obtained for wide ranges of recirculation percentage and rated filter efficiency. The program predicts: changes of airborne dust mass flowrates and concentrations both in return air and in the air being re-introduced into the intake of the ventilation system.

Data from the computer model are then presented in graphical formats. These demonstrate the possible benefits of recirculation towards airborne respirable dust.

1 INTRODUCTION

Ventilation, as a prerequisite of underground mining, is necessary to dilute and remove the pollutants that are introduced into the mine atmosphere. These not only include the common gases, solids and vapours but also extreme heat or cold.

As a means of enhancing ventilation recirculation has been suggested and has since been the subject of both extensive research and field trials. In both of these, consideration of gas contaminants and heat aspects has been predominant.

1.1 The definition of recirculation as applied to mine ventilation

For the mining environment, it is only being proposed and considered that truly controlled recirculation be employed.

The definition given by Jones (1983) for recirculation is "the movement of the same body of air more than once past a given point in a ventilation system." He also emphasized that this method is widely used in domestic and industrial heating, ventilation and air conditioning (HVAC). An ammendment to this should be 'the movement of part of an original body of air more than once ....'.

Recirculation is induced by 'booster' fans. Norris and Walker (1982) stated a further condition to the definition "A booster fan controlled recirculation system is stipulated as a fan installation causing the recirculation of a prearranged, continuously monitored, proportion of return air ."

1.2 The concept of recirculation

The basic concept of recirculation is shown in fig. 1 (Hardcastle, Kolada & Stokes,1984). A mine ventilation system has inherent leaks which tend to reduce the amount of air reaching the working place, which leads to inadequate ventilation and the associated difficulties outlined in fig. 1a.

Depending on how and where recirculation is introduced the volume flow through a working place may be increased, firstly, by virtue of a natural leakage path being removed and, secondly, by the recirculated amount, (fig. 1b.). Where a new airway is used no leakage is regained.

The benefits of recirculation can include; improved fresh and total air quantities, increased air velocities, improved pollutant mixing and increased air cooling powers.

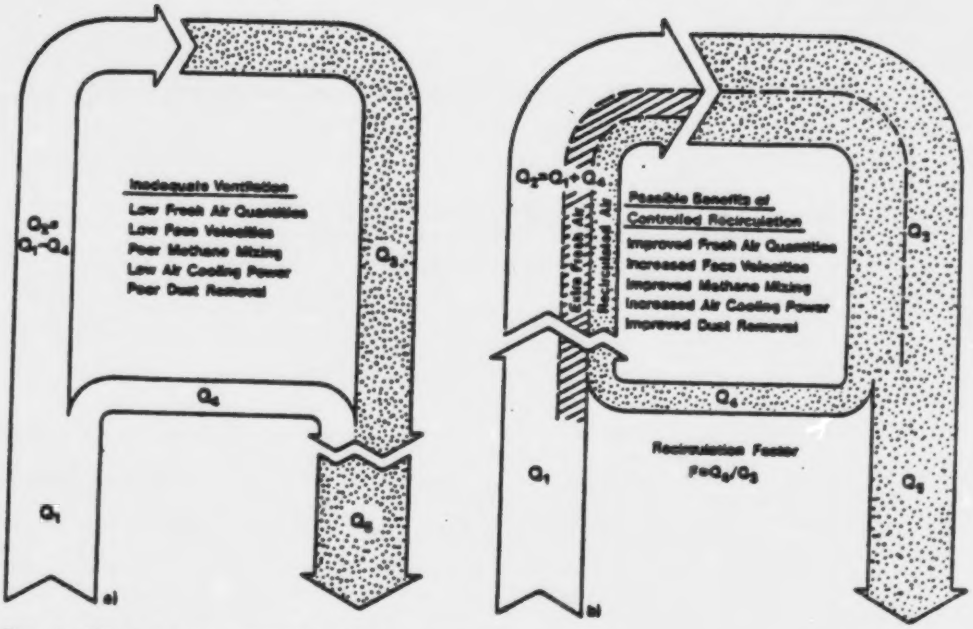

Inadequate Ventilation
Low Fresh Air Quantities
Low Face Velocities
Poor Methane Mixing
Low Air Cooling Power
Poor Dust Removal
$Q_2 = Q_1 - Q_4$
Q_3
Q_4
Q_1
Q_5
a)
$Q_2 = Q_1 + Q_4$
Extra Fresh Air
Recirculated Air
Possible Benefits of Controlled Recirculation
Improved Fresh Air Quantities
Increased Face Velocities
Improved Methane Mixing
Increased Air Cooling Power
Improved Dust Removal
Q_3
Q_4
Recirculation Factor
$F = Q_4/Q_3$
Q_1
Q_5
b)

Fig. 1. Diagrammatic representations of airflows under a) conventional and b) recirculatory ventilation (Hardcastle, Kolada & Stokes, 1984).

As a point of reference it is necessary to define recirculation quantitatively, and a standard measure common to most studies is the recirculated fraction or factor. This theoretically has the range 0 to 1.0, and it is often converted to a recirculation percentage.

The rationale adopted here, with reference to fig. 1b, is :

(i) Recirculation factor, F

$$F = Q_4/Q_3 \qquad (1)$$

in which Q_4 = the recirculated quantity
Q_3 = the quantity flowing in the return directly inbye of the recirculation path

(ii) Recirculation percentage

$$= F \times 100 = Q_4/Q_3 \times 100$$

2 HISTORY OF RECIRCULATION

Studies and trials only pertaining to recirculation on a large-scale are discussed, Hardcastle (1983) demonstrating that heading recirculation regimes were generally dissimilar. Heading recirculation has already been widely employed and is the subject of numerous publications.

2.1 Coal-mine applications

Recirculation as proposed here was first suggested for coal-faces (Leach & Slack, 1969). Generally any ventilation system has difficulties in maintaining adequate airflows at the work-place as mines continually develop. In coal mines convectional ventilation circuits are becoming so long and extensive that only limited improvements are possible even if they were economically viable. Such improvements include airway enlargement, airway duplication and satellite shafts.

A preliminary feasibility study into the wider application of controlled recirculation in coal-mines was performed between 1979-82, (Stokes,1982), (Kolada,1982), (Hardcastle,1983), (European Communities Commission,1983), (Lee & Longson,1984).

The first coal-mine trial of controlled recirculation was performed at Wearmouth colliery, U.K., July 1983, (Pickering & Robinson,1984). This is an undersea mine with working areas presently 7.5 km from shaft bottom and expected to exceed 11 km in the future.

The field trial and the feasibility study proved the following effects (summarized) :

A)There should be sufficient fresh air to dilute gaseous pollutants produced both inside and outoye of the recirculation area to acceptable levels, regardless of the recirculated amount.

B)Providing A) exists then the gaseous pollutant concentrations in the general body of the air in the recirculation area will reach a maximum value above which they will not increase.

C)It is predominantly the mixed-intake containing the recirculated air whose gaseous pollutant concentration will increase in relation to the recirculation factor.

D)The airflow required, apart from gaseous pollutant considerations, is also determined by optimum air velocities. These are important for dust control, dispersion of methane layers, and reducing effective temperatures.

E)The air velocity required for D) can be obtained using recirculation without increasing returnside gaseous pollutant concentrations to undesirable levels.

2.2 Metal-mine applications

Van Der Walt (1978) suggested recirculation for the hot, deep metal-mines of S. Africa. Here the objectives were; to reduce the amount of tertiary and secondary cooling; to fully utilise airways; and to provide better control over the distribution of cooling.

Conversely, in cold climates recirculation could be used to conserve heating. This could form a major cost saving in such places as Alaska and Canada.

A major field trial at Loraine Gold Mine again demonstrated that recirculation was a practical, effective and safe aid to normal ventilation practice (Burton, Plenderleith et al,1984). Here attention was given to combining the benefits of controlled recirculation with refrigeration and dust control. The recirculation percentage was normally 68% and a spray chamber was used to remove airborne dust from the recirculated fraction. This field trial of over 1 year duration has proved effective for temperature and dust control with no major new procedures required for its use. This trial also demonstrated again that recirculation per se will not cause a general increase of contaminant concentrations in the return air.

Blast contaminant decay proved itself to be an exponential function related to the fresh air flow. This is similar to steady state produced pollutants but with a time integration included.

The Loraine trial was successful in using recirculation to control dust and distribute cooling. Here only gas control remains to dictate the fresh air ventilation levels.

3 AIRBORNE RESPIRABLE DUST AND CONTROLLED RECIRCULATION

The theory for gaseous pollutants in a recirculation circuit for steady state conditions, equations 1-6, are already well documented. The theory with respect to respirable dust is not totally analogous to a gaseous contaminant.

Apart from the inclusion of filtration (Burton et al,1984), (Jones,1983) in the steady state gas equations little other consideration has be given to dust excepting Hardcastle (1983).

Recirculation will increase the air velocity; this in turn controls dust mass flows. Velocity can increase the air's dust dispersion efficiency from a source (Hall,1950), (Ford,1975); then once airborne, in association with the dust's size and concentration, it can also cause human discomfort, (Vincent & Gibson, 1980), (Gibson & Vincent, 1980), (Ford, 1975). Numerous other parameters also control dust availability and generation prior to entering the airstream (National Coal Board,1978), (European Communities Commission,1978)

Unlike gasses airborne dust can be deposited. The mechanisms causing this are dependent on air velocity and particle size.

Deposition and filtration are the two mechanisms which control concentrations once the dust is airborne and will be very significant in a recirculation circuit, thus the theory for dust is more complex than for gases.

Using a simplified model the desired preliminary estimate of the likely effects of controlled recirculation on airborne dust is obtained.

3.1 Relevant field studies to model dust

Theoretically values for deposition can be calculated for the mechanisms of gravitational and inertial settling, and diffusion (Knight & Hardcastle,1985), however, when compared, these are much less than the field values of Reinhardt (1972) and Ford (1976). The field studies, figs. 2 & 3, detail dust transportation through coal-faces and along return mine

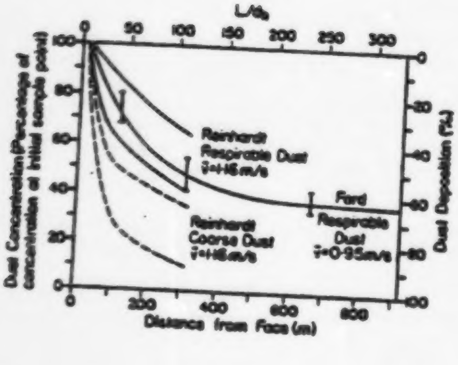


Fig. 2. The reduction of airborne dust concentrations along mine roadways (Ford, 1976;Reinhardt,1972)

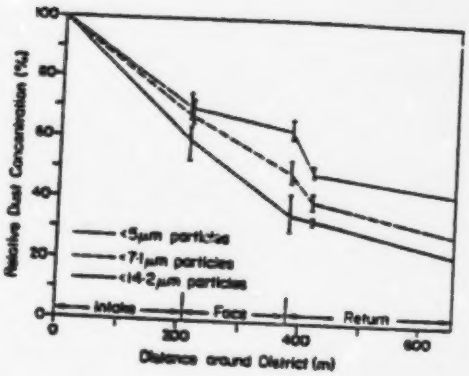


Fig. 3. Deposition of sized fractions of stone dust through a district (Ford,1976).

airways. In fig. 2 the agreement between the two researchers is good, the curves show rapid deposition of relatively new dust over 300 m dependent on size. With increasing age of the dust cloud the rate of deposition exponentially decays. For respirable dust up to 60% of that introduced at the face will be lost within 600 m of the return gateroad.

Figure 3 shows the deposition around a district of tracer dust (stonedust) introduced at the intake. This again shows the size dependency of dust deposition and its exponential decay with age of the dust. In this instance the deposition is much less in the return airway. For <7.1 um uda stonedust the system deposition was 70%.

These two field studies show deposition as a major airborne dust removal mechanism. As such this could be extremely significant where dust laden air is being re-used.

It is generally envisaged that a controlled recirculation system should include dust filtration of the recycled air. In the Loraine test a spray chamber was employed.

Filtration, as with deposition, is a size selective process with the larger sizes being predominantely removed. James (1979) performed tests with two identical MRDE high capacity filters in-line, and showed that the efficiency of the second filter was 50% of the rated value. This resulted from the second filter cleaning an airborne dust cloud of much finer composition.

The decay of a filter's efficiency on a second, third or fourth pass could be extremely important in a recirculation circuit where a proportion of the airborne dust will be filtered more than once.

3.2 Dust modelling with recirculation

Figure 4 shows the basic terminology used for dust modelling in a recirculation area. For simplification all dust producing sources in the recirculation area have been summed to a single input, d.

Dust sedimentation in the recirculation area has been assumed to act the same as a mechanical filter and treated as such.

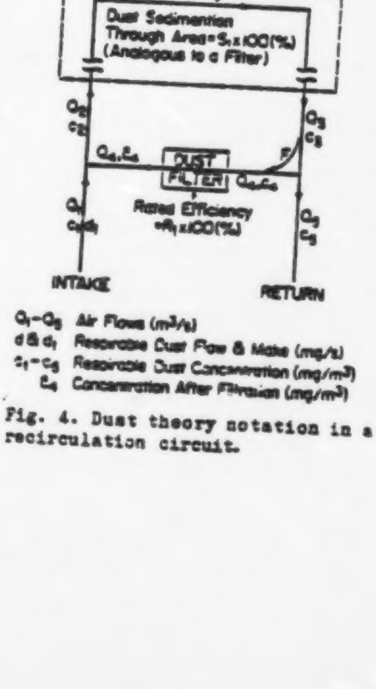

Pollution Zone:
Contains all Dust Sources,
Summed to Single Production Rates
d
Dust Sedimentation
Through Area=S_1x100(%)
(Analogous to a Filter)
Q_2
c_2
Q_3
c_3
Q_4,c_4
DUST FILTER
Q_4,c_4
F
Rated Efficiency
=R_1x100(%)
Q_1
c_1,d_1
Q_5
c_5
INTAKE
RETURN
Q_1–Q_5 Air Flows (m^3/s)
d & d_1 Respirable Dust Flow & Make (mg/s)
c_1–c_5 Respirable Dust Concentration (mg/m^3)
c_4 Concentration After Filtration (mg/m^3)

Fig. 4. Dust theory notation in a simple recirculation circuit.

General recirculation, (x = pollutant contribution):

$$F = \frac{Q_3}{Q_4} \quad (1) \qquad Q_2 = \frac{Q_1}{(1 - F)} \quad (2)$$

$$Q_3 = Q_2 = \frac{Q_1}{(1 - F)} \quad (3) \qquad Q_4 = FQ_3 = \frac{FQ_1}{(1 - F)} \quad (4)$$

$$C_2 = \frac{(C_1Q_1 + Fx)}{Q_1} \quad (5) \qquad C_3 = \frac{(C_1Q_1 + x)}{Q_1} = C_4 = C_5 \quad (6)$$

Standard geometric composition, (Subscripts, T and i, denote total and initial values):

$$Q_{3T} = Q_1 + FQ_1 + F^2Q_1 + \ldots\ldots + F^nQ_1 = Q_1/(1 - F) \quad (7)$$

$$d_{3T} = d_{3i} + Fd_{3i} + F^2d_{3i} + \ldots\ldots + F^nd_{3i} \quad (8)$$

$$d_{3i} = d_1 + d$$

Including filtration, R:

$$d_{3i} \text{ is unaffected} = d_{3i}f^0(1 - R)$$

$$Fd_{3i} \longrightarrow (1 - R_1)Fd_{3i} = d_{3i}f^1(1 - R)$$

$$F^2d_{3i} \longrightarrow (1 - R_1)(1 - R_2)F^2d_{3i} = d_{3i}f^2(1 - R)$$

Substituting in (8)

$$d_{3T} = d_{3i}\left[1 + F.f(1 - R) + F^2.f^2(1 - R) + F^3.f^3(1 - R) \ldots\ldots + F^n.f^n(1 - R)\right] \quad (9)$$

$$d_{3T} = d_{3i}\left[f\{F , f(R)\}\right] = d_{3i}\left[f(F , R)\right] \quad (10)$$

Including sedimentation, S:

$$d_{3i} \longrightarrow (1 - S_1)(d_1 + d) = f^1(1 - S).(d_1 + d)$$

$$Fd_{3i} \longrightarrow F(1 - S_1)(1 - S_2)(d_1 + d).f(1 - R) = f(1 - R).f^2(1 - S).F(d_1 + d)$$

$$F^2d_{3i} \longrightarrow F^2(1 - S_1)(1 - S_2)(1 - S_3)(d_1 + d).f^2(1 - R) = f^2(1 - R).f^3(1 - S).F^2(d_1 + d)$$

Substituting in (8)

$$\begin{aligned} d_{3T} = {} & f(1 - S).(d_1 + d) + f(1 - R).f^2(1 - S).F(d_1 + d) + f^2(1 - R).f^3(1 - S).F^2(d_1 + d) \\ & + f^3(1 - R).f^4(1 - S).F^3(d_1 + d) \ldots\ldots + f^n(1 - R).f^{(n+1)}(1 - S).F^n(d_1 + 1) \quad (11) \end{aligned}$$

Removing $(1 - S_1)(d_1 + d)$ or d_{3i} from each term

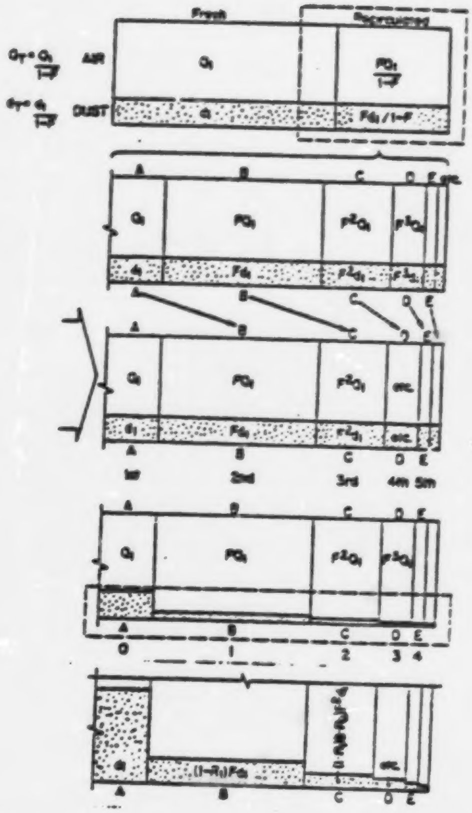
$$\begin{aligned} d_{3T} = d_{3i}[& 1 + F.f(1 - R).f^{*}(1 - S) + F^2.f^2(1 - R).f^{2*}(1 - S) + F^3.f^3(1 - R).f^{3*}(1 - S) \\ & \ldots. + F^n.f^n(1 - R).f^{n*}(1 - S) \quad (12) \end{aligned}$$

* Sedimentation, $(1 - S_1)$, already removed in d_{3i}, equations start with $(1 - S_2)$.

$$d_{3T} = d_{3i}[f\{F , f(R , S)\}] = d_{3i}[f(F , R , S)] \quad (13)$$

$$c_{3T} = d_{3i}\frac{[f(F , R , S)]}{Q_3} = d_{3i}\frac{[f(F , R , S)].(1 - F)}{Q_1} \quad (14)$$

$$c_{4T} = c_{3i}[f'(F , R , S)] \quad (15) \qquad c_{2T} = (1 - F)c_1 + Fc_{4T} \quad (16)$$



Basic two element composition for dust and airflow in the recirculation area. Initial assumption of no losses reduces both to a summated geometric series.

Enlargement of the recirculation section depicts theoretical series composition for dust and air assuming no losses.

After one complete circuit of the recirculation area there is a new input of dust and air, and old elements have all been reduced by the recirculation factor, F, e.g. Q_1 becomes $F.Q_1$ etc.

Pass number around the circuit.

Including a dust filter in recirculation path of the circuit reduces the amount of recirculated dust. Dust no longer reduces as a geometric series.

Pass number through the dust filter.

Enlarged dust section shows the effects of filter removal on each element. The filtration efficiency decays for each pass through the filter.

Fig. 5. Block representation of the theoretical air and dust composition under recirculation as a series of elements and the selective effects of filtration on each element.

Theoretically the air flowing in the recirculation circuit can be shown to be made up of elemental parts that are on their first, second, third, etc. pass through the system, fig. 5. Each of these elements is increasingly smaller as it is repeatedly cut by the recirculation factor. At steady state these form the components of a geometric series, equation 7.

The airborne dust recirculation theory is based on the same premise, equation 8. Element parts have been recirculated an increasing number of times and each recirculation reduces the size of the element. Initially dust production is assumed constant and not affected by the changes of air velocity induced with recirculation.

The theoretical composition of air and dust flows described in equations 7 & 8 and depicted initially in fig. 5 do not account for filtration or deposition in the circuit.

Introducing a filter to the system, as in fig. 4, will reduce the amount of dust being introduced from the return to the mixed-intake. For the elemental analysis given here, in association with each element being progressively reduced by the recirculation factor, the dust in those elements is also increasingly removed by filtration; fig. 5 and equation 9 show the theoretical effects. In equation 9 the filtration operator is maintained as a function to include filter efficiency decay for each pass. Generally the dust flow in the return during recirculation is the product of the dust being produced and entering the area and a function of the recirculation factor and filter efficiency, equation 10.

Treating sedimentation as a filter allows it to be similarly included, operating an increasing number of times for each pass around the circuit, equations 11 to 13. In equation 12 the sedimentation function starts at the value for the second pass as the original is already accounted for in the dust mass. This last form is used to determine the final return concentration, equation 14.

Another concentration of prime interest is that of the mixed-intake, c_2, fig. 4; this can not be as easily determined as it is controlled by, and a combination of, the availability and quality of fresh air and the recirculated fraction. By a similar treatment to that for the return-side the quantity of dust escaping through the filter and its concentration in the air, $\hat{c}_4$, may be found, equation 15.

Equation 16 gives the simplest form for calculating the mixed-intake concentration, this assumes that the fresh airflow does not increase with recirculation.

4 COMPUTER PREDICTION OF DUST CONCENTRATIONS UNDER RECIRCULATION

To fully evaluate the inter-relationship of recirculation factor, filter efficiency, sedimentation rates and possible decay of the latter two on dust concentrations necessitates extensive calculation. This is best suited to a computer.

A computer program has been written for the IBM PC. The two primary relationships used are; one, equation 12, for return dust mass flow and the other for dust mass in the cleaned air being mixed with the intake air. The program also calculates the dust in air concentrations for these masses and any change of rated filtration efficiency.

Input data required by the program are; the sedimentation factor, the decay rate of filter efficiency on each pass through the filter and the decay rate of sedimentation on each pass through the system. All three of these inputs have a 0 to 1.0 range.

For any set of input parameters, the output from the program is normally in a 10 x 11 tabular format, relating, for example, how the return dust concentration varies for the full range of filter efficiencies (0 to 1.0, i.e. 100%), and a practical range of recirculation factors (0 to 0.9, i.e. 90%). Both are incremented in 0.1 steps.

Contoured graphical plots of the tabled data may be produced using standard contouring packages. These can require a smaller increment, (i.e 0.025 or 37 x 41 table), between points to interpolate between and provide smooth curves.

The program presently assumes that the decay rates are constant, for example extrapolating from filter tests (James, 1979), where the second filtration efficiency was half that of the first; the third would be half the second, the fourth half the third and so on, that is for a 0.5 decay rate.

Similar to mechanical filtration, sedimentation may be expected to reduce as the age of the airborne dust increases and size decreases; this is demonstrated in figs. 2 & 3.

As both dust removal mechanisms are size selective, both can be expected to interact and cause a general reduction in efficiency even before one recirculation is complete.

4.1 Computed example of the effects of recirculation on dust concentrations

In the following analysis the input parameters were;

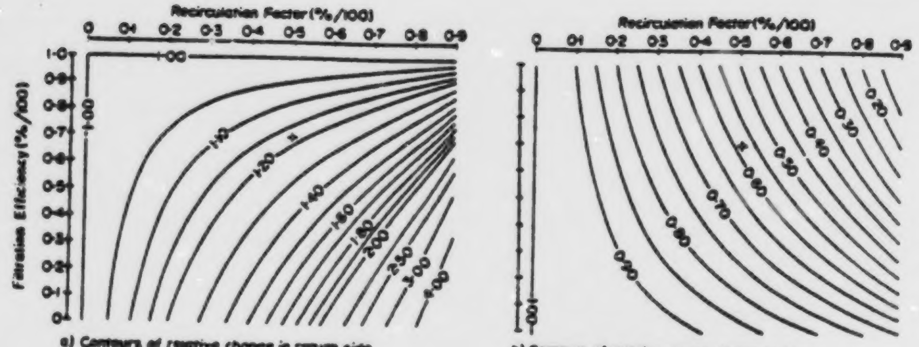
a)Sedimentation was conservatively entered as 0.4(40%), this is lower than that found in field tests but in those studies there was no interaction with a filter.

b)The decay rate of filter efficiency was taken as 0.5(50%) throughout the analysis; this agrees with filter studies for the second pass. The decay rate probably does vary in later passes, assuming it remains constant will only produce small errors as the actual elements at this stage are also small.

c)The decay rate of sedimentation was also taken as 0.5(50%) throughout the analysis. As with to the mechanical filter it is assumed to stay constant.

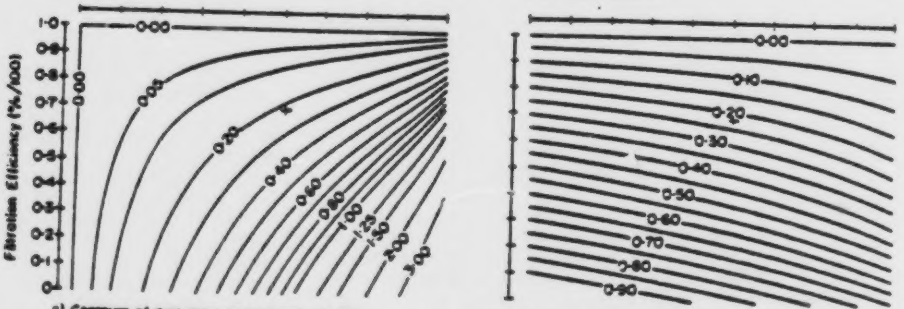
The above assumptions are not expected to cause any greater inaccuracies in the theoretical equations than already exist due to the limited information available.

Figures 6a to 6e are contour plots of the computer predicted data for the above parameters; these all assume dust production is constant and not affected by the increased air velocity. Figures 6a & 6c are the primary dust mass plots from the central two series equations of the program, both are relative to the original dust flow in the return: for fig. 6c the original dust flow in the recirculation path is of no consequence. The mass flows are converted to concentrations for figs. 6b & 6d; these have been related to the initial return concentration c_5 directly outbye of the recirculation path and assumes that the fresh air flow Q_1 has not increased. If no recirculation path previously existed as a leakage path then the concentration changes relate to the



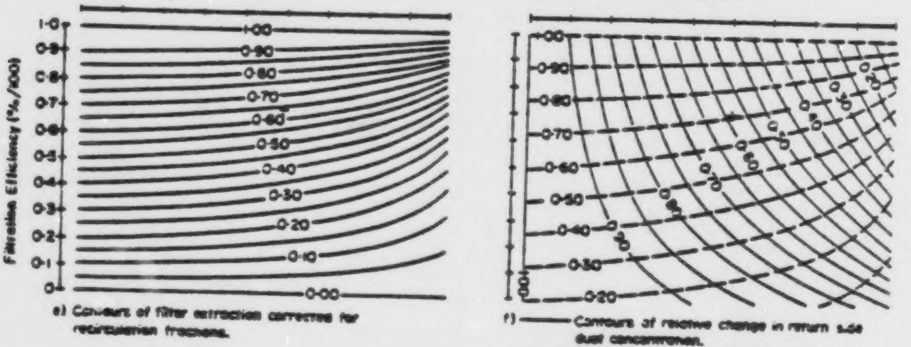
a) Contours of relative change in return side dust flow by mass.

b) Contours of relative change in return side dust concentration.



c) Contours of dust mass passed through filter relative to return mass flow.

d) Contours of dust concentration passed by filter relative to return concentration.



e) Contours of filter extraction corrected for recirculation fractions.

f) ——— Contours of relative change in return side dust concentration.
——— Contours of maximum dust increase relative to velocity for same concentration.

Fig. 6. Computer predicted contours showing the relative effects of recirculation with filtration, over conventional ventilation, on dust mass flows and concentrations; a) to e) assume no increase in dust make, f) indicates the make increase limit related to air velocity improvement for concentrations not to increase. (Input parameters - sedimentation factor = 0.40, filtration decay per circuit = 0.50, sedimentation decay per circuit = 0.50).

initial return concentration c_3.

From the dust mass flows it is also possible to determine how much dust is being removed by the filter and thus its efficiency. This will demonstrate how filtering previously filtered dust with recirculation causes the overall efficiency to be lower, fig. 6e.

The last contour plot, fig. 6f, is a composite; superimposed over the return concentration plot, as in fig. 6b, are contours of the proportional increase of dust mass flow, relative to the proportional increase of air velocity necessary to maintain the same concentration in the return.

4.2 Analysis of contour plots

From fig. 6 the following may be obtained;

1)Recirculation increases the mass of dust flowing in the return airway. This is irrespective of filtration and sedimentation efficiencies.

2)Due to filtration and sedimentation dust does not remain in the general air body as with a gas; this will produce a disproportionate increase of air flow in relation to dust and results in a general reduction of return air dust concentrations. This is providing dust makes do not increase.

3)Similar to the return the relative increase of dust flow entering the fresh air stream even after the filtration can be significant.

4)The airflow increase in the recirculation path is also disproportionate to the dust increase, thus after the filter the air being recycled is relatively clean; in certain instances the filtered air can be much cleaner than the normal intake air and so provide better dust conditions in the mixed-intake.

5)The rated filter efficiency gradually decays with increasing recirculation.

6)Figure 6f introduces the option of dust mass flow rates increasing with velocity; this demonstrates that if dust make increases faster than velocity then the return concentration will deteriorate, however depending on filter efficiency and recirculation factor a limited increase may occur without an increased concentration.

4.3 Theoretical example

Using the plots of fig. 6 the following example has been worked. Initial dust and airflow conditions were:

1) Intake concentration, $c_1 = 0.5$ mg/m^3
2) Return concentration, $c_3 = 1.0$ mg/m^3
3) Fresh air (no leakage), $Q_2 = Q_1$
4) Air velocity = 1.5 m/s

Recirculation conditions were:

5) Recirculation factor, $F = 0.50$(50%)
6) Filter efficiency, $E_1 > 0.70$(70%)
7) Fresh air unchanged

The air velocity increase was given by $F/(1 - F) = 1$, i.e. 100% or doubled. The following was obtained from each part of fig. 6 in turn, initially assuming no dust make increase:

a) The returnside dust mass flow will increase by up to 18%, (1.18 - 1).100.

b) The actual return concentration will reduce to at most 0.58 of its former value, 0.58 mg/m^3.

c) Of the dust flowing in the return only 0.22(22%) re-enters the intake as compared to 50% for the air.

d) The relative concentration of dust in the cleaned air will be up to 23% of the return, that is, 0.23 mg/m^3.

e) The minimum in situ filter efficiency with recirculation has reduced from 70 to 64%.

f) Using equation 16 provides the mixed-intake concentration as 0.365 mg/m^3 for no increase of dust make.

g) With a 100% increase of velocity, a 71%(0.71x1.0x100) increase in dust make would cause the return concentration to remain unchanged at 1.0 mg/m^3.

h) Recalculating d) & f) for an increased dust make of 71%; the cleaned air concentration will be 0.39 mg/m^3 and the mixed-intake concentration 0.44 mg/m^3.

5 DISCUSSIONS

The above treatment deals with the respirable dust cloud as a whole and accounts for size dependent filtration and deposition through the use of decay factors. An alternative method would have been to use actual filtration or deposition efficiencies on specific size ranges and apply them at each recirculation and change towards a finer size distribution. The accuracy or merits of either method will only be proven with more field studies and trials. The second requires greater detail and longer computation.

This analysis, although relatively simple, indicates how recirculation will affect dust concentrations. Generally it may be seen that good filtration is necessary, this being especially important when the dust make increases. Dust make should be controlled to as little as possible by avoiding sources. For a system with a good filter, dust make and air velocity can virtually increase at the same rate without causing higher concentrations in the system than occurred prior to recirculation. In the Loraine test (Burton et al), with 68% recirculation, the ore production in the area trebled while an acceptable concentration was maintained in the return.

For air velocities under 4 m/s, (a human comfort level from dust impaction) it can be generally assumed that dust make does not greatly increase with velocity. Therefore recirculation with a filter should always provide better return respirable dust conditions. Improved intake dust conditions are also possible when the filtered air is cleaner than the natural intake.

The quantitative benefits of a specific recirculation regime should always be checked through theoretical analyses to indicate how respirable dust concentrations are affected. The above analysis predicts the general concentrations either side of the recirculation path and not necessarily at the working place. With judgement it can be applied to work places but care is necessary when anti- and homotropal ventilation are being evaluated. However, this analysis has adequately demonstrated that dust concentrations can be controlled by a recirculation system.

In recirculation systems it remains the gaseous pollutants that control the acceptability of the system. Dust, heat, temperature and refrigeration, although important, are secondary.

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4.24

Section 4 – Chapter 24

A Simple Method for Determining Size Distribution of Airborne Dust by Its Settling Velocity

by

G. Knight

American Industrial Hygiene Association Journal

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MÉTHODE SIMPLE DE DÉTERMINATION DE LA DISTRIBUTION GRANULOMÉTRIQUE DES POUSSIÈRES EN SUSPENSION DANS L'AIR BASÉE SUR LA VITESSE DE SÉDIMENTATION

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Le présent rapport décrit une méthode graphique simple utilisable en laboratoire ou sur le terrain pour déterminer les paramètres de la distribution granulométrique à partir de mesures gravimétriques ou autres relatives aux poussières recueillies par des échantillonneurs munis de sélecteurs granulométriques (élutriateurs horizontaux). La technique est illustrée par quelques résultats obtenus au laboratoire, et une comparaison est faite avec les résultats obtenus pour les mesures granulométriques effectuées au moyen du compteur de Coulter.

A Simple Method for Determining Size Distribution of Airborne Dust by Its Settling Velocity

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This report describes a simple field or laboratory graphical technique for determining the size distribution parameters from gravimetric or other measurements of dust collected by samplers fitted with size selectors (horizontal elutriators). The technique is illustrated by some results obtained in the laboratory and is compared with results obtained with Coulter counter size measurements.

THE SIZE DISTRIBUTION of airborne dust is important in two respects: firstly, insofar as it affects the deposition of dust in the bronchial passages and the penetration to the alveolar region of the lung; and secondly, as it affects the action of the portion deposited in the alveolar region. The mechanism of dust deposition in the bronchial passages and the alveolar region of the lung are impaction, settlement, and diffusion, and for each particle the probability of its being deposited at a given site is dependent on its aerodynamic properties. The "aerodynamic size" is used as a measure of these properties and is defined as the diameter of a unit-density sphere having the same settling velocity in air as the particle in question.

This paper is concerned with determination of the size distribution parameters as they affect penetration through the bronchial passages to the alveolar region of the lung—that is, in the 1- to 10-μm aerodynamic size range. The bulk of the mass and surface area of the dust deposited in the alveolar region is associated with particles in this size range.

Yankovskii and Fuks[1] showed that, if the size distribution of an airborne dust cloud can be represented mathematically, the parameters describing it can be determined by measurements with a set of consecutive cyclones. They also stated that many industrial dusts can be represented by a logarithmic-normal size distribution.

This paper presents a technique and a graph for the determination of the parameters of a logarithmic-normal size distribution using horizontal elutriators in parallel instead of cyclones as size selectors. Horizontal elutriators possess the advantage that their size selection is expressed by a simple theory[2] which has been confirmed experimentally.[3]

Theory

A dust sampler fitted with a horizontal elutriator size selector consists, in its usual form, of a number of rectangular channels through which air flows horizontally, followed by a filter paper to collect the "respirable" dust. The airborne dust particles settle toward the floor of each channel under the action of gravity. Some of these particles reach the floor and adhere.

The theory of horizontal elutriators was given by Walton,[2] who showed that, in the size range below a critical maximum size x_E (the design top-cut of the elutriator), the proportion of particles of a given size that settle out in a rectangular channel is proportional to their settling velocity. The top size cut is that size corresponding to a particle that will just fall the height of the channel during the period of time required for the air to flow from one end of the channel to the other. Since the settling velocity is proportional to the square of the aerodynamic size, x, the proportion of size x, settling out is given by

$$p = x^2/x^2_E \quad \text{for } 0 < x \leq x_E \qquad (1a)$$

Since all particles of size greater than x_E settle out in the elutriator, we may write

$$p = 1 \qquad \text{for } x > x_E \qquad (1b)$$

where x is the aerodynamic size of the particle and x_E is the design top-cut of the elutriator.

The proportion, p', of particles of size x passing through the elutriator and collected on the filter paper for assessment as "respirable" dust is

$$p' = 1 - (x^2/x^2_E) \quad \text{for } 0 < x_E \qquad (2a)$$

and

$$p' = 0 \qquad \text{for } x > x_E \qquad (2b)$$

If the assumption is made that the size distribution of the airborne dust cloud can be described mathematically, the amount of dust settling in the size selector or collected on the "respirable" dust filter can be calculated. This is shown below for an assumed logarithmic-normal size distribution This distribution, following Herdan,[4] is given as

$$y = \frac{1}{\ln \sigma_g \sqrt{2\pi}} \exp \left[- \frac{(\ln x - \ln x_g)^2}{2 \ln^2 \sigma_g} \right] \qquad (3)$$

where x_g is the mass geometric mean size, and σ_g is the geometric standard deviation. Ln σ_g is the standard deviation of a normal distribution. By applying equation 2 to equation 3 and integrating, the amount of dust passing through the elutriator and collected on the "respirable" dust filter is given as

$$C_E = \frac{C_0}{\ln \sigma_g \sqrt{2\pi}} \int_0^{x_E} \left[1 - \frac{x^2}{x^2_E} \right] \exp \left[- \frac{(\ln x - \ln x_g)^2}{2 \ln^2 \sigma_g} \right] d \ln x \qquad (4)$$

where C_E is the dust concentration found by the sampler with elutriator and C_0 is that found by a total dust sampler.

The integral can be split into two parts and transformed to the standard probability function by using the transformations

$$y = \frac{\ln (x/x_g)}{\ln \sigma_g} \qquad (5)$$

for the first half and

$$z = \frac{\ln (x/x_g)}{\ln \sigma_g} - 2 \ln \sigma_g \qquad (6)$$

for the second half. Then

$$C_E = \frac{C_0}{\sqrt{2\pi}} \left[\int_{-\infty}^{Y} \exp \left(\frac{-y^2}{2} \right) dy - \frac{x^2_g}{x^2_E} \exp (2 \ln^2 \sigma_g) \int_{-\infty}^{Z} \exp \left(\frac{-z^2}{2} \right) dz \right] \qquad (7)$$

where the upper limits are

$$Y = \frac{\ln (x_E/x_g)}{\ln \sigma_g}$$

$$Z = \frac{\ln (x_E/x_g)}{\ln \sigma_g} - 2 \ln \sigma_g$$

The value of the integral

$$\frac{1}{\sqrt{2\pi}} \int_{-\infty}^{x} \exp \left(\frac{-x^2}{2} \right)$$

dx is given as $P(x)$ in the *Handbook of Mathematical Functions.*[5] In this form the dust concentration found by a sampler with elutriator is given by

$$C_E = C_0 \left[P \left(\frac{\ln (x_E/x_g)}{\ln \sigma_g} \right) - \frac{x^2_g}{x^2_E} \exp (2 \ln^2 \sigma_g) P \left(\frac{\ln (x_E/x_g)}{\ln \sigma_g} - 2 \ln \sigma_g \right) \right] \qquad (8)$$

This integral was evaluated for a range of values of the ratio x_E/x_g and of the standard deviation σ_g. Then by graphical interpolation the contours of equal fractional collection by a size-selective dust sampler, C_E/C_0, were prepared and plotted in Figure 1, where the vertical axis is the standard deviation of the logarithmic-normal distribution and the horizontal axis is the ratio of the top-cut aerodynamic size of the elutriator to the mediam aerodynamic size of the dust cloud, x_E/x_g.

Method for Determination of Size-Distribution Parameters

A dust cloud with a logarithmic-normal distribution is described by three parameters—concentration, the geometric mean size, and the geometric standard deviation. To determine these it is essential to make measurements with instruments having three or more size-selection characteristics. It is usually convenient to use an open filter measuring the total airborne dust as one of these, and the technique is presented in a form suitable for this. (Added in proof: Graphs have since been prepared for calculating logarithmic normal size distributions without using an open filter sampler and are available from the author.) The ratio of the dust concentration, estimated by the size-selective samplers, to the total airborne dust concentration is calculated and used.

The parameters of the logarithmic-normal size distribution are read off Figure 1 by the technique shown in Figure 2. *Step 1*: Prepare a copy of the horizontal scale marked at the points $(1/x_{E,1})$, $(1/x_{E,2})$, etc., where $x_{E,1}$, $x_{E,2}$, etc., are the top-cut sizes of the elutriators used. *Step 2*: While maintaining this copy of the scale in a horizontal position, obtain the best fit between the points $(1/x_{E,1})$, etc., and the corresponding dust concentration ratio for each elutriated sample. *Step 3*: Read off the standard deviation, σ_g, on the vertical scale and the median size at the position on the horizontal axis corresponding to 1 on the sliding scale. The units of the median size are the same as

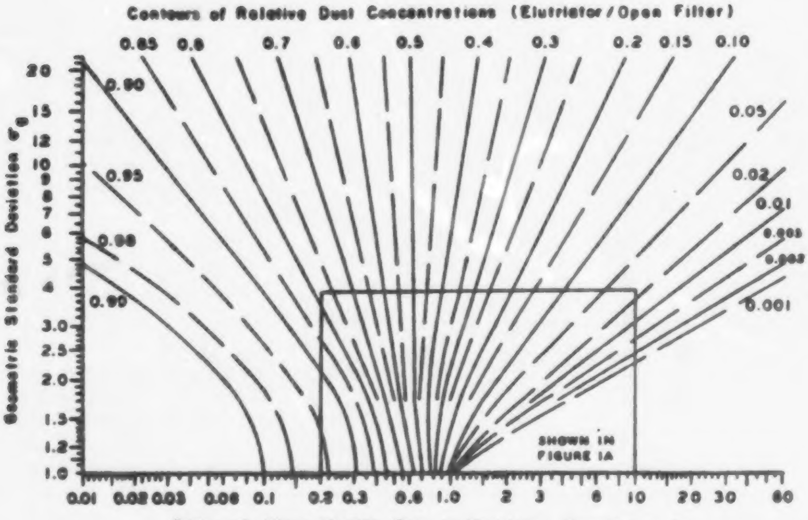

Figure 1. Contours of relative concentrations indicated by dust samplers fitted with elutriators (top-cut size x_E) in log-normal dust clouds.

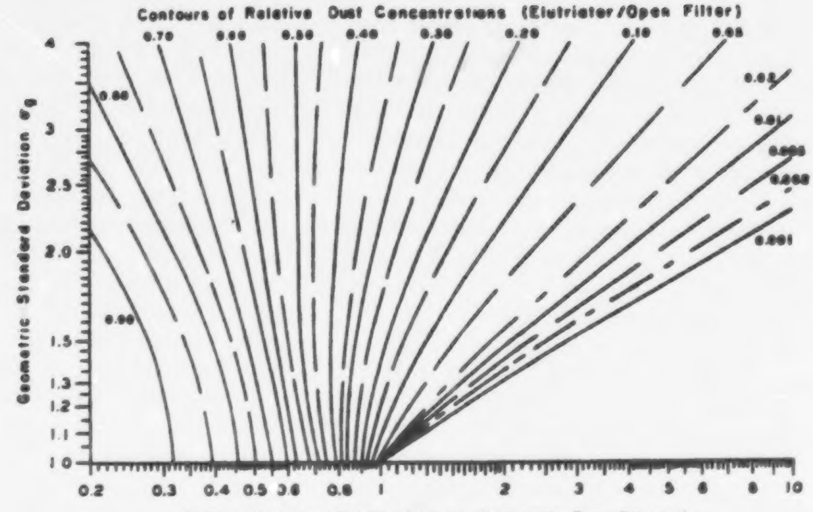

Figure 1A. Enlarged central region of Figure 1.

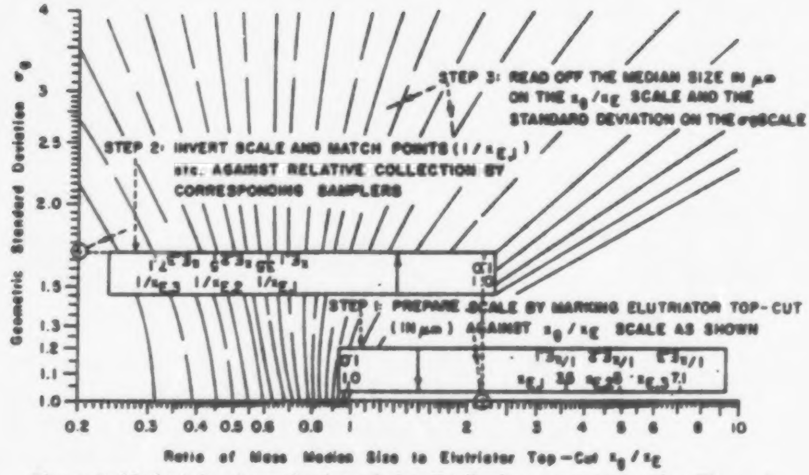

Figure 2. Method for determination of size-distribution parameters using Figure 1.

those of x_E.

Test Results

This method for determination of size distributions was tested by using an open filter and four samplers with elutriators—top-cuts of 9.65, 7.1, 5.1, and 3.6μ—in a number of laboratory dust clouds. In the course of these tests it became apparent that appreciable errors occurred in dust deposition in some of the samplers with elutriators; this appeared to be due to dust deposition in the sampler between the elutriator and the filter holder. To elucidate these irregularities, a number of elutriator-filter arrangements were compared. Figure 3 shows the arrangements of each unit and the relative dust concentration obtained when operated at a flow rate to give a cutoff, x_E, of 7.1 μm. These tests demonstrated the best methods of operating the existing samplers with elutriators, and samples were taken in a number of dust clouds.

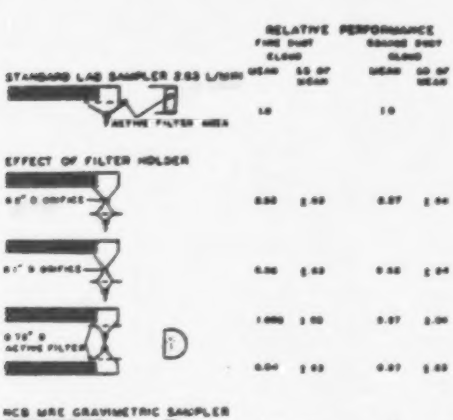

Figure 3. Schematic diagrams and relative performance of respirable dust samplers.

The results obtained are shown in Table I. The mass median aerodynamic size and geometric standard deviation were derived by using the open filter and the coarsest and finest size-selective samplers. The middle four columns give the results obtained with the other two samplers with elutriators, together with the values derived from the other samplers. It can be seen that the agreement between these pairs of values is reasonable, indicating that the assumption of a logarithmic-normal size distribution is adequate for calculating dust deposition in the size range examined.

The results obtained on the standard laboratory dust clouds were compared with results obtained previously on the same type dust cloud using a Coulter counter. These are given in Table II. The agreement between the two methods is reasonable, as the Coulter counter does not measure particles less than 1.5 μm (equivalent volume diameter) and the corrections for undersize particles are probably in error.

Discussion

This technique gives a simple measurement of the size distribution in airborne dust insofar as it is likely to affect the penetration of dust to the lungs. The aerodynamic size range of interest is 2 to 10 μm. In mixed dust clouds, the assumption of a logarithmic-normal distribution may not be adequate, and the use of samplers with more than three size-selection characteristics can be helpful. As 10 μm is the coarsest dust of interest, it is also the top-cut of the largest elutriator of interest, and the lower limit of top-cut usable is about 3 μm.

The technique is not limited to determining dust concentration in terms of mass, and any parameter could be used. For example, the dust could be collected on membrane filters and counted under a microscope or the amount of quartz determined by x-ray analysis. In the latter case, the results would give the size distribution of the quartz rather

TABLE I
Experimental Determinations of Particle Size Distribution Using Size-Selection (Horizontal Elutriation) Sampler

Dust Cloud	Ratio of Dust Concentrations HE/Open Filter, C_s/C_o, at Top-Cuts, x_s, of:						Mass Median Aerodynamic Size x_g (μm)[a]	Geometric Standard Deviation, σ_g[a]
	9.6	7.1		4.9		3.5		
		M[a]	D[a]	M[a]	D[a]			
Coal	0.85	0.78	0.75	0.645	0.62	0.44	2.55	2.0
(jet-milled)	0.91	0.82	0.82	0.685	0.68	0.46	2.45	1.6
	0.91	0.81	0.82	0.655	0.68	0.46	2.45	1.6
Coal	0.62	0.48	0.46	0.32	0.31	0.18	4.8	1.95
(no cyclone)	0.59	0.465	0.43	0.30	0.285	0.16	5.0	2.0
Pyrite	0.91	0.82	0.84	0.74	0.75	0.63	1.7	2.3
(jet-milled)	0.84	0.74	0.745	0.56	0.63	0.46	2.4	2.2
	0.83	0.72	0.73	0.57	0.58	0.41	2.75	1.95
Pyrite (no cyclone)	0.4	0.275	0.26	0.15	0.15	0.07	7.4	2.0
Asbestos (jet-milled)	0.73	0.72	0.705	0.67	0.66	0.62	0.9	18
Uranium ore	0.348	0.23	0.225	0.130	0.135	0.063	8.8	2.2
(EDCP[b] 1)	0.400	0.263	0.255	0.145	0.145	0.065	7.6	2.0
(EDCP 2)	0.334	0.219	0.22	0.124	0.135	0.067	9.1	2.3
	0.322	0.226	0.215	0.124	0.135	0.267	9.4	2.35
	0.334	0.219	0.22	0.114	0.135	0.064	18.9	2.2
	0.322	0.216	0.22	0.122	0.135	0.068	9.2	2.25
(EDCP 3)	0.281	0.18	0.18	0.111	0.11	0.057	10.7	2.4
	0.29	0.19	0.185	0.120	0.12	0.058	10.4	2.35
Diabase								
(EDCP 2)	0.363	0.241	0.245	0.164	0.165	0.090	8.8	2.5
(EDCP 3)	0.376	0.257	0.26	0.172	0.17	0.095	8.2	2.4
Limestone	0.336	0.222	0.22	0.125	0.13	0.066	9.2	2.25
(EDCP 3)	0.322	0.204	0.21	0.124	0.13	0.062	9.4	2.3
Coal	0.352	0.194	0.205	0.119	0.105	0.042	8.4	1.9
(EDCP 3)	0.342	0.197	0.20	0.116	0.10	0.038	8.5	1.9

[a] The values of x_g *and* σ_g are derived by best fit for (C_s/C_o) at x_s of 9.6 and 3.5. The other columns-give measured values (M) and for comparison values derived (D) from x_g *and* σ_g using the graph.

[b] Three experimental dust-cloud production methods under test.

TABLE II

Comparison of Logarithmic-Normal Size Parameters by Horizontal Elutriator Sizing (HES) and by Coulter Counter

Dust Cloud	HES		Coulter Counter		
	Mass Median Aerodynamic Size (μm)	Standard Deviation	Volume Median Size (μm, by volume)[a]	Corrected Median Size (VMS • $\sqrt{\rho}$)[b]	Standard Deviation
Coal					
Jet-milled	2.5	1.7	1.75	2.1	1.6
No cyclone	4.9	2.0	5.7	6.9	2.1
Pyrite					
Jet-Milled	2.75	1.95	1.9	4.2	1.8
No cyclone	7.4	2.0	3.5	7.8	1.9

[a] The volume median size is the diameter of a sphereof which 50% of the particles have a larger volume.

[b] The corrected median size is equal to $\sqrt{\rho}$ volume median size, where ρ is the density to bring to aerodynamic size, neglecting shape factors.

than that of the total airborne dust; this may be of considerable interest because quartz deposited in the lungs is a great hazard to health.

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Section 4 – Chapter 25

Application of EDXRF Analysis to the Determination of Metallic Elements in Airborne Mineralogical Dusts

by

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Application of EDXRF Analysis to the Determination of Metallic Elements in Airborne Mineralogical Dusts

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Résumé

La fluorescence de rayons X à dispersion d'énergie (FRXDE) a été utilisée pour analyser des métaux contenus dans des poussières ramassées à l'aide d'impacteurs CAMPED à membrane d'argent. Seuls les éléments dont les raies K et L se situent entre 4 et 18 keV ont été analysés et l'argent a été utilisé comme cible secondaire.

La sélection de particules de taille "respirable" a eu pour effet fortuit de minimiser les effets de taille de particules et d'absorption pour les mesures par FRXDE. Les exactitudes relatives et les limites pratiques de détection sont surtout limitées par l'exactitude de la technique de soustraction du bruit de fonds. Les limites de détection en l'absence de forts recouvrements spectraux sont d'au moins un ordre de grandeur inférieurs aux valeurs seuils proposées pour des poussières aéroportées contenues dans un échantillon d'un mètre cube (1 m³) d'air. Des exactitudes relatives de 10 à 20% sont obtenues à des niveaux en-dessous des valeurs-seuils. Les techniques d'étalonnage sont décrites et des modifications facultatives sont suggérées pour augmenter les sensibilités pour certains éléments et pour étendre la technique à d'autres éléments.

Abstract

Silver secondary-target EDXRF spectrometry is used to determine metallic elements having K or L analyte fluorescences between 4 and 18 keV that are present in airborne mineralogical dusts sampled by means of CAMPEDS impactors having silver-membrane filters.*

Selection of "respirable" sized particulate by the CAMPEDS has fortuitous consequences for the EDXRF measurements, since particle size and absorption effects are minimized. Relative accuracies and practical detection limits are found to be mainly determined by the accuracy of the spectral background-stripping technique employed. In the absence of strong spectral overlap, detection limits correspond to at least an order of magnitude below threshold limit values (TLVs) proposed for airborne dusts for a 1 m^3 air sample. Typical relative accuracies of the order of 10 to 20% are indicated at levels considerably below TLVs. Calibration techniques are described and optional modifications are suggested to increase sensitivities for particular elements and to expand the scope to other elements.

Introduction

The monitoring and control of respirable air quality in workroom environments of the mining and mineral processing industries are receiving increased attention as the knowledge of the effects of occupational environments on health improves and as relevant sampling and measuring techniques are developed. Threshold limit values (TLV®) in terms of mg m^{-3} of particulate in air have been recommended as maximum acceptable levels for a variety of chemical products and mineral substances and are periodically revised (1).

Aerodynamic particle size (2) has an important role in the physiological fate of inhaled dust since particulates with aerodynamic diameters larger than about 7 or 8 μm are largely deposited in the upper respiratory tract, while smaller particles have a higher probability of reaching sites in the

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*Energy-Dispersive X-Ray Fluorescence

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lungs (3). Accordingly, size-selective sampling is being used with more frequency, and increasingly inertial cascade impactors (2) are being chosen. The Canadian Mining Personal Dust Sampler (CAMPEDS), developed at the Mining Research Laboratory, CANMET, consists of a two-stage impactor/air sampling system powered by a miner's-light battery. The first two impaction stages reject supra-10 μm particles and the respirable particulate material is then collected on a silver-membrane filter (4). This system has undergone extensive testing and is currently being used to survey silica levels in airborne mine dusts using X-ray diffraction measurements.

The objective of the present work was to examine the potential of EDXRF to measure other elements in particulate matter collected with the CAMPEDS system, thereby expanding the information available as to the content of airborne mine dusts. The principal advantages of EDXRF over other available analytical techniques is that collected samples can be examined directly with the potential for broad-range multi-element analysis with good sensitivity in reasonable analysis times. The investigative approach was to develop calibration techniques to potentially measure 20 elements whose K or L fluorescent lines lie between the K_α and L_α fluorescences of the silver membrane backing material, and to apply these procedures to determine a more restricted range of observable elements that are present in CAMPEDS-sampled airborne dusts generated from a variety of test reference ores, thereby observing the effects of sampling and measurement on the results.

Experimental

Sample Preparation

1. Dust Chamber Technique. Sub-74 μm source-samples were fed continuously to a twin-jet fluid energy mill and then exhausted into a 20 m^3 dust chamber. The airborne dust was sampled simultaneously by five CAMPEDS units operated at 2 L min^{-1} until pressure differentials across the collection membrane indicated loadings of the order of 1 mg. Tared 5 μm pore-size silver membranes (Selas FM-25) were used for collection, and deposit weights were determined using a semi-microbalance. The circular deposits have an area of 3.14 cm^2. Details of the collection system are described elsewhere (4).

2. Wet-Grind Technique (4). Samples were dry-ground in a mortar to sub-44 μm and a 50 mg portion was then wetted with ethanol and ground for a further 5 to 10 minutes. This finely-ground suspension was transferred with 50 mL of ethanol to a cylindrical vial to produce a suspension column about 10 cm in height. The vial was capped, shaken thoroughly, uncapped, and allowed to stand for 3 minutes. If relatively large amounts of sedimentation occurred, the suspension was decanted, and the sediment rinsed on the mortar with 2-3 mL ethanol, reground, then returned with the suspension to the vial and the above process repeated. A tared 0.8 μm pore-size silver membrane (Selas FM-25) was mounted in a suction filtration apparatus, and the 10 cm filtration column was loaded with 1:1 ethanol/water. After the settling period, a 1.0 or 2.0 mL aliquot was extracted from the centre of the vial, drained onto the top of the filtration column, and immediately drawn onto the filter by suction. The loaded filter was removed, dried for 30 minutes at 100°C and the deposit weight determined on a microbalance.

3. Laboratory Airborne Technique. The vacuum jar dust-generating and sampling apparatus described by Giauque *et al.* (5) was modified to accommodate a CAMPEDS unit containing a tared 5-μm silver membrane. Milligram quantities of sub-44 μm source powder were loaded into the jar, the system was evacuated via the CAMPEDS unit, and a dust cloud created by venting one or two short bursts of air into the container. Airborne dust was drawn through the CAMPEDS by the pumping system. Deposit weights were determined with a microbalance.

4. Preparation of Thin Films of Copper and Lead Metals. Vapours of copper and lead were condensed on 3.14 cm^2 circularly-masked areas on tared thin Mylar® film using an Edwards 6.E.2 Coating Unit equipped with a Speedivac oil diffusion pump. Foils of copper and lead of 100 and 71 μg cm^{-2} respectively were mounted over 0.8-μm silver membranes for EDXRF measurements.

5. Sample Mounting for EDXRF Measurements. The loaded silver membranes were mounted between two layers of thin Mylar® film on the face of a 1.25-inch diameter polyethylene sample cup to ensure presentation of a planar surface to the spectrometer, and to avoid loss of sample.

6. Mineralogical Dust Source-Materials. Reagent grade metallic oxides and sulphides were used for calibration purposes. Test samples were generated

from Canadian Certified Reference Materials Project (CCRMP) materials. These included: DH-1, a uranium ore; UM-1, a nickel/copper/cobalt-containing ultramafic rock; KC-1, a zinc/lead/tin ore; RU-1, a zinc/copper ore; CD-1, an antimony/arsenic ore; and CCU-1, CZN-1, and CPB-1, respectively copper, zinc and lead concentrates of sulphide-based ores. Details of the mineralogy and chemical compositions are available in CANMET publications (6).

7. Preparation for Atomic Absorption Spectrophotometric (AAS) Determinations. Following EDXRF measurement, the mounted silver membrane and Mylar® film cover were removed from the sample cup and dissolution of the filter and sample was effected as follows. Dust adhering to the Mylar cover was dislodged by rinsing briefly in 3 mL of hot 1:2 nitric acid in a Teflon® beaker and finally with a fine jet of 2-3 mL of water, after which the film was discarded. The silver membrane and readily-soluble particulate were dissolved in 2 mL of warm 1:1 nitric acid in a 100 mL glass beaker, and the suspension then diluted to 10 mL with water and allowed to cool to room temperature. Insoluble particulate was separated from the solution by suction-filtration through a 0.45-μm pore-size Millipore® HA membrane filter followed by jet-rinsing of the beaker with 15 mL of water. The filtrate obtained was returned to the glass beaker and evaporated gradually to 3-4 mL while the following procedure was carried out.

The Millipore® filter containing insoluble particulate was transferred to the Teflon® beaker and a further 3 mL of nitric acid added. The solution was evaporated to about 1 mL on a hot plate in a perchloric acid fume hood to decompose the filter. Water (1 mL), nitric acid (1 mL), 48% hydrofluoric acid (3 mL), and 70% perchloric acid (1 mL) were then added, and the solution was evaporated to the appearance of fumes of perchloric acid. The beaker sides were rinsed down with 2-3 mL of water, and the solution was evaporated to 0.1 to 0.2 mL and cooled. The warm evaporated filtrate was then transferred quantitatively to the Teflon® beaker, rinsing with a minimum of water and the combined solution was then warmed and then cooled to 20°C, and finally quantitatively transferred to a 10 mL volumetric flask, diluted to volume and mixed thoroughly. These solutions were submitted to the Ores and Fire Assay Section, Chemical Laboratory, CANMET for AAS determination of iron, copper, lead, and zinc. Blank values, obtained by carrying unused silver membranes through the above procedure, correspond to 9 ± 5, 5 ± 1, 3 ± 1, and 5 ± 2 μg, respectively.

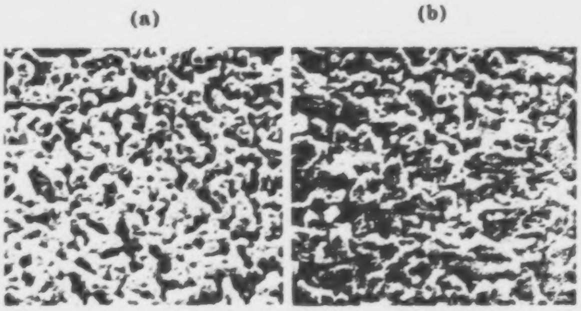


Figure 1. SEM secondary electron images of 0.8 μm pore-size silver membranes: a) empty, b) 0.215 mg cm^{-2} copper oxide (wet-grind method). Photo diameter corresponds to 67 μm.

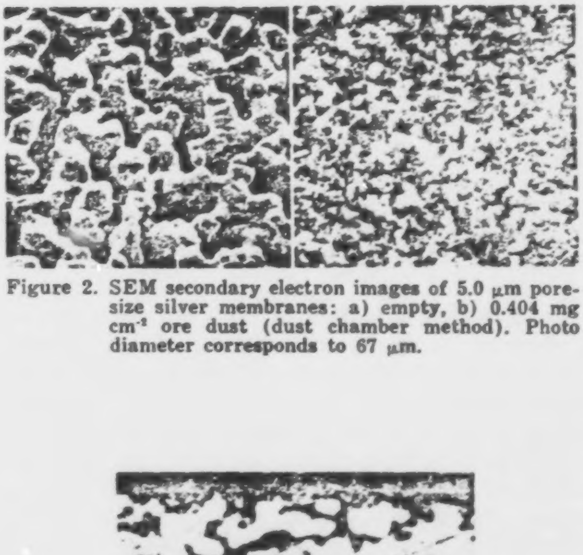


Figure 2. SEM secondary electron images of 5.0 μm pore-size silver membranes: a) empty, b) 0.404 mg cm^{-2} ore dust (dust chamber method). Photo diameter corresponds to 67 μm.

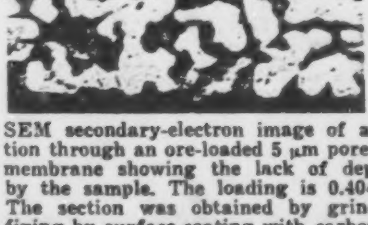


Figure 3. SEM secondary-electron image of a cross-section through an ore-loaded 5 μm pore-size silver membrane showing the lack of depth-loading by the sample. The loading is 0.404 mg cm^{-2}. The section was obtained by grinding after fixing by surface-coating with carbon and then setting in an acrylic plastic. Photo diameter corresponds to 96 μm.

SEM Measurements

Scanning electron microscopy was used to obtain secondary-electron images of the surface topography of loaded and unused silver membrane filters. The measurements were obtained by Dr. R. Packwood of the Physical Metallurgy Research Laboratories, CANMET, and are presented in Figures 1-3 and discussed later in the text.

X-Ray Fluorescence Measurements

1. **Instrumentation.** Fluorescence measurements were made using a KEVEX Subsystem-0810 EDXFR spectrometer having a 30 mm² Si(Li) detector exhibiting 170 ~~k~~eV resolution at 5.9 keV and featuring selectable secondary-target excitation. A KEVEX KE422607 tungsten anode X-ray tube powered by a Philips PW-1140 generator provided primary excitation. Signals were processed by a KEVEX 4532P pulse processor/amplifier and then input to a Tracor-Northern TN-1700 pulse height analyzer equipped with a 1024 channel memory and various ROM data manipulations functions. Spectra were smoothed by applying the smoothing function, a five-point Savitsky-Goulay fit, prior to output to a Texas Instruments Silent-700 terminal where they were stored on magnetic tape in either spectral or integrated region-of-interest (ROI) formats. Data were transferred to a CDC Cyber 74 computer for mathematical treatment or to obtain hard copy plots with a peripheral CALCOMP plotter.

2. **Operating Conditions.** The tungsten tube was operated at 35 kV, 4 mA to excite a silver secondary target. The fluorescence beam from this target was filtered by a 3-mil Ag/10-mil Al sandwich foil to provide AgK exciting radiation to the sample. Fluorescent radiation from approximately 80% of the sample surface was detected using an 8 mm collimator. Spectra were acquired over the range 2.50 to 27.6 keV (24.5 eV/memory channel) for a fixed live time (LT) of 800 s; typical clock-times (CL) were 1100 s. Integral ROI's spanning 0.60 keV about the centroid energies of analyte fluorescences were set as follows: K_α: Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Se, Sr, Y, Zr, Mo, L_α: U. L_β: Pb, Th($L_{\beta1}$), Bi (13.01 to 13.31 keV). Compton-scattered AgK radiation was monitored from 20.01 to 20.65 keV and used for background calculations. Spectra of fifteen samples and a brass sensitivity monitor were acquired sequentially in an automatic program mode generated by the TN-1700.

3. **Calculations.** Net integrated intensities (N_i) were extracted by a FORTRAN IV program using the following principles. It was deduced that the contribution of scattered radiation to the background intensity at a given ROI (B_i) was adequately measured as a linear function of the measured Compton region (I_{Ag}):

$$B_i = D_i I_{Ag} + E_i.$$

Contributions due to overlap or peak-tailing by fluorescent lines of other elements (B_i') were considered to be proportional to the final net intensity of the analyte fluorescence of the interfering element (N_j):

$$B'_i = \sum_j F_{ij} N_j.$$

The constants D_i/E_i and F_{ij} were determined by linear regressions of data obtained from membranes loaded with individual element oxides. The process of extraction of net intensities in multicomponent samples is then:

$$I_i = ROI_i - D_i I_{Ag} - E_i$$
$$N_i = I_i - \sum_j F_{ij} N_j.$$

Simultaneous solution of the twenty equations is performed by an on-line callable library subroutine, MAS004 (7), which determines values of N_i that minimize the sum-of-squares of the fit errors (R_i):

$$\sum_i R_i^2 = \sum_i (I_i - \sum_j F_{ij} N_j - N_i)^2$$

The net intensities obtained from individual oxides and sulphides were used to derive sensitivity parameters in terms of intensity/μg element/mg sample, and these were used directly for determinations.

Results and Discussion

SEM Examination of Loaded Membranes: Implications for EDXRF

Details of the structure of the silver membranes and typical sample loading properties are revealed in secondary-electron images (Figures 1-3). Figures 1a and 2a show the cross-linked "dumbbell" structure and regular pore-size of the membranes. Figure 1b shows a typical deposit obtained by the wet-grind technique; particle sizes are rather non-uniform, ranging from about

0.7 to 7 μm in diameter, a typical particle being of the order 4 μm in diameter. Figure 2b shows a CAMPEDS-sampled dust, generated from an ore with the jet-mill/dust chamber. Here, the particle size range is more uniform, about 0.7 to 4μm particles are observed. Figure 3 shows details of a cross-section through the same filter, obtained after fixing the sample with an acrylic. The sample is revealed to be confined to the collection surface of the membrane, and not partially residing within the porous structure. It was also confirmed by backside measurements that no material was trapped deep in the porous structure. Figure 2a shows that the surface pore structure is considerably blocked by particle agglomerates, effectively reducing the pore-size as loading proceeds. Evidently, particulate that is sufficiently fine to pass the surface is sufficiently fine to pass entirely through the filter.

The above observations have important implications with regard to EDXRF measurements. Strong X-ray absorption by the silver membrane structure would render sub-surface particles inaccessible to measurement. Additional measurements, designed to correct for absorption by light-element filter material (5, 8, 9), are inoperable for the same reason. Consequently, it is fortuitous that the particulate is impacted at the surface, and the membrane may be regarded as a "perfect-screen" filter for purposes of EDXRF (8). The presence of an analyte in different minerals gives rise to X-ray absorption differences which cause variations in the sensitivity. As illustrated in Table I, calculations based on the perfect screen model predict that such effects are expected to be minor for loading that are less than about 0.5 mg cm^{-2}. It is also apparent from calculations, and verified by examination of the SEM images, that the samples are "thin" (10), and interparticle screening of X-rays is negligible.

Particle-size selection by both the CAMPEDS/dust chamber and wet-grind techniques is such that variable effects of particle-size on the X-ray response will be small. Table II shows predicted relative sensitivities as a function of particle size as calculated for several oxides (10), where published densities are considered to apply. The effect is most pronounced for high density, heavy-absorber materials. Frequently, however, fine particulate matter consists of agglomerates or flocculi exhibiting much lower densities (2b); this would tend to reduce this effect. Furthermore, the CAMPEDS-sampled particles have a characteristic mean "aerodynamic" diameter of the order of 3 or 4 μm (4); corresponding physical diameters are smaller in proportion to the reciprocal of the square root of their densities (2). Consequently, it is expected that particle-size effects on the X-ray sensitivities should be very small, and more or less constant.

Table I. Computed Relative Mineralogical Absorption Effects Based on the Perfect Screen Filter Model

Fluorescence	Mineral	I mineral/I oxide*
Fe K_a	pyrite	1.00
Fe K_α	arsenopyrite	0.95
Zn K_α	sphalerite	0.99
Mo K_a	molybdenite	1.00
Pb L_β	galena	1.00

*Calculated from Equations 3 and 5 of Reference 8, with Ag K_α excitation, 45°/45° spectrometer geometry, the absorption coefficients of Reference 11, and mass loadings corresponding to 0.318 mg cm^{-2} of the oxide.

Table II. Calculated Effects of Particle Size on Sensitivity (10).

Particulate	Density g/cm^3	Sensitivity Factor* diam. μm: 0.2	1	2	5	10
TiO_2	4.26	.996	.98	.96	.90	.81
Fe_2O_3	5.18	.996	.98	.96	.91	.84
CuO	6.4	.996	.98	.96	.90	.82
ZnO	5.61	.996	.98	.96	.91	.84
MoO_3	4.69	.997	.99	.97	.93	.87
PbO	9.53	.987	.94	.88	.73	.56

*Computed from equation 12.10, reference 10, using the mass absorption coefficients of reference 11.

Calibration, Sensitivity, and Detection Limits

It was considered desirable to establish the fluorescence-response calibration by using the dust-chamber technique, so that field-sampling conditions would be modelled. However, a major problem prevented direct calibration using this technique; contamination between preparations was evident in the fluorescence spectra of ostensibly pure individual oxides and sulphides despite extensive intermediate purging. This is now explainable as being due to charge build-up during the jet-milling stage with a subsequent electrostatic precipitation of charged particulate in the system ductwork. The particulate is eventually released at unpredictable rates as the charge is lost. Unfortunately complete system decontamination between successive runs was not practical, in view of the number of samples to be run.

Table III. Wet-Grind Method: Fluorescence Sensitivities Derived From Oxides and Sulphides (0.8 µm Ag Filters, 800 s Live Time)

Material	Net Counts/µg Element	Measured Precision, RSD	No. Filters
TiO_2	19	8.2	2
V_2O_5	27.0	0.5	2
MnO_2	51	17.0	5
Fe_2O_3	67	1.3	3
FeS_2	58	3.6	2
Co_2O_3	72	---	1
NiO	96	3.2	2
Cu film	137	1.5	1
CuO	128	4.6	3
ZnO	144	6.8	3
ZnS	149	4.8	3
As_2O_3	249	8.0	2
Y_2O_3	380	3.0	2
MoO_3	479	2.7	3
MoS_2	429	4.5	2
Pb film	122	---	1
PbO	104	6.4	3
PbS	99	3.3	3
Bi_2O_3	62	6.0	2
ThO_2	113	5.0	2
$UO_2(Ac)_2 \cdot 2H_2O$	172	---	1

Table IV. EDXRF Analysis of Dust Chamber-Deposited Oxides and Sulphides

Material	% Purity[a)]	% Contaminants Measured[d)]									Sensitivity[b)]	Precision,[c)] RSD
		Fe_2O_3	CuO	ZnO	As_2O_3	MoO_3	MoS_2	Bi_2O_3	PbO	ThO_2		
TiO_2	100										17.9	5.2
MnO_2	100										40.6	0.8
CuO	63.8				4.3	0.3		30	1.6		117	6.3
As_2O_3	93.8		6.2								227	6.6
MoO_3	90.8		1.4		7.8						516	1.8
ZnO	86.8		0.9		1.3	11.0					161	1.8
ZnS	78.0		1.3	?	11.5	9.2					171	1.6
PbO	96.8			1.6	1.3	0.3					110	2.4
PbS	97.4			0.8	1.6	0.2			?		109	1.9
Fe_2O_3	83.1			2.5		0.9			13.5		57	10.5
Bi_2O_3	98.1			0.4	1.0	0.1			0.5		60	1.7
ThO_2	98.1							1.9			118	2.4
Y_2O_3	73.0		0.8					2.6		23.6	33.3	0.6
MoS_2	81.2	0.6	0.6					1.3		16.3	403	1.2
FeS_2	78.0		2.8		2.4		2.0	1.5		15.5	49	3.0

a) 100%-sum of contaminants measured; b) counts per microgram of element per 800 s live time; c) 5 replicate filters measured; d) oxide form of contaminant assumed where both oxides and sulphides were deposited previously.

Nonetheless, very useful information was derived from these preparations. In fact, the X-ray measurements confirmed that standards prepared by the wet-grind technique were applicable to airborne samples. Fluorescence sensitivities obtained from samples of individual oxides and sulphides prepared by the wet-grind technique are recorded in Table III. In contrast to corresponding materials prepared in the dust chamber, no contamination was evident in the spectra. These sensitivities were used to measure the amounts of contaminants observed in the spectra of material prepared in the dust chamber, and thereby obtain the weight of oxide or sulphide that was nominally deposited. Corresponding sensitivities were then derived from the dust chamber samples with these corrected weights. The observations are summarized in Table IV. The derived sensitivities are in good agreement with those obtained by the wet-grind method given the reproducibilities of net intensities obtained for replicate preparations and the consequent potential for additional error introduced by the contaminant measurement.

Despite rather large standard deviations for replicate preparations, samples prepared by the laboratory-airborne method yield results in good agreement with the other techniques. These variances are believed to arise largely from radially uneven deposits and possibly the presence of oversize particulate due to the fast, unregulated air-flow rates that were obtained.

Sensitivities observed for K_α analyte fluorescences from oxide and sulphide samples prepared by the three techniques are systematically dependent on energy relative to the excitation energy as shown in Figure 4, and as predicted for thin specimens with monochromatic excitation (5). In fact, calibration for elements of intermediate atomic numbers could be accomplished by linear interpolation of values obtained from three or four standards, provided that background interferences from other analyte fluorescences can be estimated. It is also self-evident that the option of selecting the excitation radiation is advantageous for cases where a particular analyte is of interest, since the sensitivity may thereby be maximized. The analytical data of Tables III and IV and of Figure 4 also confirm that: particle size effects are minimal (metallic thin-films ex-

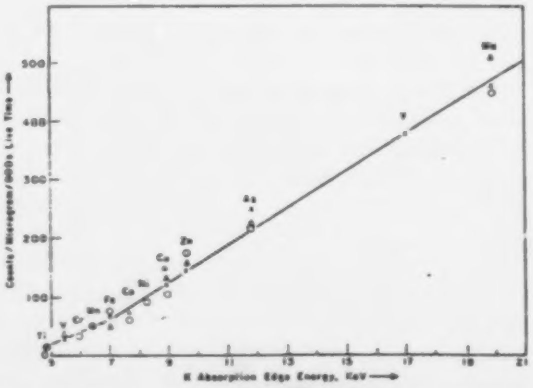


Figure 4. Mean sensitivities observed for K_α fluorescent lines of oxides and sulphides; method: (*) metal film, (X) wet-grind, △ dust chamber, ○ laboratory-airborne.

hibit marginally larger sensitivities than minerals), and absorption effects due to mineralogical variations of the analyte element should be insignificant (oxides and sulphides exhibit the same sensitivity).

Even when sample amounts are relatively large, and statistical contributions to the precision of the measured intensity are small, precisions remain of the order of 5 to 10% RSD for replicate-loaded membranes. Gross intensities obtained from a single membrane measured in a fixed orientation (no sample spinner was available) were reproducible within statistical limits. However, the same sample measured in different rotational orientation yielded RSDs of the order 3% above those expected. This indicates that physical variations in the sample surface may be contributing significantly to the precision of measurements.

Detection limits in practice are determined by the accuracy with which the spectral background can be stripped. The present sophistication of the stripping method is such that scatter backgrounds are accurate within about ± 400 counts, leading to detection limits considerably above those predicted on the basis of statistical considerations, as shown in Table V. In fact, the presence of elements can be detected by visual observation of the spectrum at levels approaching statistical limits and well below those calculable with certainty mathematically. Of course, the presence of appreciable spectral-line overlap will raise the detection limits proportionately depending on elements present and their relative amounts in multicomponent samples. Nevertheless, these detection limits are at least an order of magnitude lower than TLVs published for the presence of the elements herein in airborne dusts, assuming 1 m^3 of air is sampled (1), i.e., collection for an eight hour shift with the CAMPEDS sampler.

Table V. Detection Limits with Current Procedures

Element	Typical Scattered Background (800 s LT) [0.40 keV interval]	Practical D.L., µg (Mathematical Stripping)	Statistical D.L., µg (Visual Inspection)
Ti	5350	30	12
V	4900	22	9
Cr	4500	18	6
Mn	4000	12	4
Fe	3900	9	3
Co	3400	8	2
Ni	2900	6	2
Cu	2800	5	1
Zn	2800	6	1
As	2600	3	0.6
Se	2500	3	0.6
Sr	2650	2	0.5
Y	3250	3	0.5
Zr	4200	2	0.5
Mo	7300	1	0.5
Pb	2700	6	1.5
Bi	1400	10	2
Th	4600	5	2
U	2700	4	0.9

Table VI. Analysis of CAMPEDS-Sampled Ore Dusts

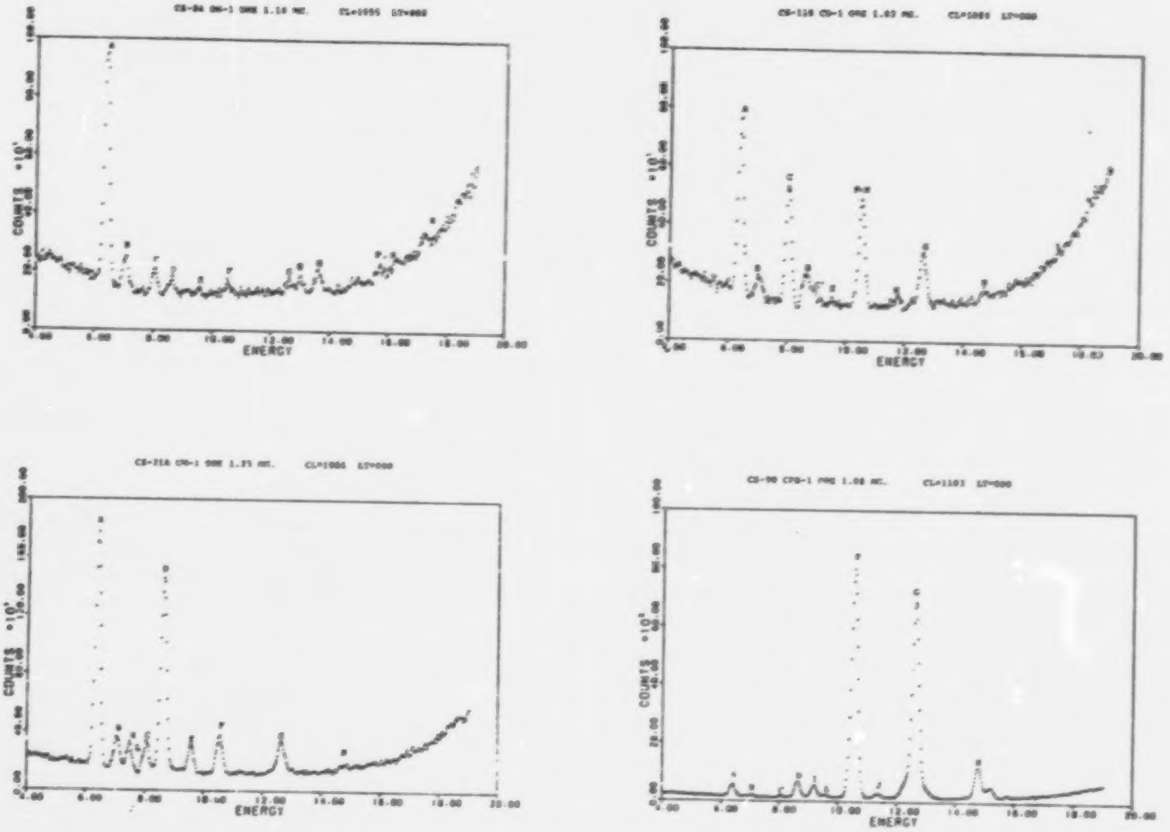
	Sample, µg (RSD**, %), AAS, [Ore, nominal]***						
Ore	Fe	Cu	Zn	Pb	Sn	As	U
[illegible]	90(6), 97 [.61]	6.7(8), 3.0 [?]	*, 0.9 [?]	*, 3.6 [?]			5.6(8) [1.72]
CZN-1	112(4), 102 [109]	*, 6.7 [1.44]	637(3), 549 [647]	127(5), 119 [76.5]			
[illegible]	175(5), 146 [136]	12(9), 13 [4.4]	88.1(6), 48 [8.3]	18.6(5), 11.5 [?]	12(5) [0.8]		
[illegible]	157(3), 135 [153]	*, 6 [1.1]	238(6), 190 [201]	144(4), 109 [60.7]			
MP-1	203(6), 236 [244]	13.5(5), 13 [8.9]	31(8), 33 [22.6]				
CPB-1	96(5), 61 [56.3]	*, 6 [3.8]	30(5), 32 [44.3]	771(3), 656 [667]		6.2(6) [3.6]	
CCU-1	303(5), 280 [300]	288(4), 188 [287]	41(8), 35 [33.3]	18.5(8), 10 [1.06]			
[illegible]	84(8) .70]	12.3(8) [<0.1]	7.2(13) [?]	31.3(8) [8.3]		5.1(12) [0.6]	

*Below quantitative detection limit; **relative standard deviation, %, for 5 replicate samples; ***computed from source ore composition.

Test Multicomponent Dusts

Representative spectra of CAMPEDS-sampled multi-component dusts generated from reference ores in the dust chamber are shown in Figures 5. Amounts of elements determined are recorded in Table VI.

Because of the contamination problem discussed earlier, and the dependence of the aerodynamic size selection in part on particle density, collected samples do not necessarily have the quantitative composition of the source materials. Incidentally, the latter consideration applies to samples size-selected by the wet-grind technique since selection is then on the basis of a common Stoke's diameter which is also dependent on density (2). Accordingly, an attempt was made to confirm some of the EDXRF determinations by AAS determinations made after dissolution of the loaded membranes. Tests of this technique were carried out with membranes loaded with pure oxides by the wet-grind technique, and results were in agreement with those calculated from deposit weights within about 5% for iron, zinc, and lead, and within 12% for copper. The AAS results for the multicomponent dusts are included in Table VI, as are the nominal values calculated from the source ore composition. There is a general trend towards higher results by EDXRF than by the AAS procedure. It is possible that during the dissolution procedure required for AAS, minute amounts of refractory ore material were not dissolved but were lost on the beaker surfaces. Considering this possibility and the overall precisions of both methods, the results can be said to be in substantive agreement.



Figures 5. — EDXRF spectra of dusts generated from reference ores. Key: A, B (Fe K_α, K_β); C, C' (Cu K_α, K_β;) D, E (Zn K_α, K_β); F-J (Pb L_α, L_β, L_γ, L_ι, L_η); K, L (Ni K_α, K_β); M, N (As K_α, K_β); O, P (Th L_α, L_β); Q, R, S (U L_α, L_{β_1}, L_{β_2}). CL = clock time(s), LT = live time(s).

Conclusion

Results presented herein illustrate that EDXRF measurements can be used successfully to monitor metallic elements present in airborne mineralogical dusts with relative accuracies typically in the range 10 to 20%. Since the objective here was to develop calibration techniques for a spectral range of elements using a single measurement, sensitivities are a compromise in some cases, and some element fluorescences of interest are not excited. Improved sensitivities would be obtained for analyte fluorescences below 13 keV (particularly As, Pb, Se) by the use of a molybdenum target and analogous calibration methods. Elements with analyte fluorescences above those of silver (particularly Sb, Te) could be measured by use of a dysprosium target, for example. Nevertheless, with the present conditions, practical detection limits are well below currently proposed maximum acceptable levels for airborne dusts.

The sampling properties of the CAMPEDS system, designed to select "respirable" particulates, are fortuitously such that particle size and absorption effects that normally complicate the quantitative interpretation of EDXRF data are minimized and calibration is therefore straightforward. Use of the silver membranes is advantageous in that they are ideal backing substrates for X-ray diffraction measurement of collected airborne silica; consequently, a single sample is available to both analytical methods. The fact that collected samples remain impacted on the surface of the membrane removes a major difficulty for EDXRF; that of screening of imbedded particulates due to strong absorption by silver. A disadvantage of the silver membranes is that the Ag K fluorescences prohibitively overlap the K fluorescences of cadmium and tin; appropriate substitution of organic membrane filters would permit measurement of these elements.

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Section 4 - Chapter 26

Size Distribution of Airborne Dust in Mines

by

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CHAPITRE 31

DISTRIBUTION GRANULOMÉTRIQUE DES POUSSIÈRES EN SUSPENSION DANS L'AIR DES MINES

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RÉSUMÉ

On a recueilli la poussière en suspension dans l'air en un point dans trois mines d'uranium au moyen d'échantillonneurs à deux étages composés d'un filtre précédé de sélecteurs granulométriques dont 50 % des fractions granulométriques (taille aérodynamique) se situent entre 1,25 et 7,1 µm et d'un filtre ouvert. La poussière recueillie sur les filtres a été analysée par : 1) pesage de la poussière totale; 2) diffraction des rayons X en vue de doser le quartz et la poussière minérale; et 3) scintillation et comptage en vue de doser les produits de filiation du radon et du thoron.

On a constaté que le quartz et, supposément, la poussière minérale obéissaient à la loi normale pour les produits de fragmentation tronqués à des fractions supérieures de 7 à 20 µm. La poussière totale présentait un excédent de particules fines, la poussière non minérale (poussière totale moins poussière minérale) était en grande partie inférieure à 1,25 µm, ce qui est compatible avec les sources supposées : particules des échappements des diésels et poussière atmosphérique. Pour la précision de la méthode, aucun produit de filiation du

radon plus gros que 1,25 µm ne fut associé à la poussière. D'après des calculs approximatifs, plus de 90 % de la surface et 99 % du nombre sont associés à des particules de diamètre inférieur à 1,25 µm. Ces résultats expliquent probablement l'absence d'association des produits de filiation du radon aux poussières plus grossières.

Quelques résultats de mesures effectuées au microscope électronique sur des particules provenant des échappements des diésels sont présentés. Il est démontré que les particules principales sont sphériques, de 0,05 µm de diamètre environ, et qu'elles se présentent sous forme de particules indépendantes, d'agglomérats et d'amas d'agglomérats. On croit que les particules des échappements des diésels constituent la plus grande partie des particules en suspension dans l'air de la fraction granulométrique 0,03 à 1 µm dans les mines où il y a du matériel à moteur diésel.

CHAPTER 31

SIZE DISTRIBUTION OF AIRBORNE DUST IN MINES

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ABSTRACT

The airborne dust at one site in each of three uranium mines was collected on two-stage samplers consisting of a filter preceded by size selectors with 50% aerodynamic size cuts ranging 1.25–7.1 μm and an open filter. The dust on the filters was assessed by (1) weighing for total dust; (2) X-ray diffraction (XRD) for quartz and mineral dust; and (3) scintillation and counting for radon and thoron daughters.

It was found that the quartz and, presumably, the mineral dust, followed the normal law for breakage products truncated at top sizes of 7 to 20 μm. The total dust showed an excess of fine particles, the nonmineral dust–total minus mineral–was mostly <1.25 μm in size, consistent with its suspected origins–diesel exhaust particulates and atmospheric dust. Within the accuracy of the method no radon daughters coarser than 1.25 μm in size were attached to the dust. Approximate calculations suggest that >90% of the surface and 99% of the number are associated with particles <1.25 μm in diameter. This probably explains the lack of attachment of radon daughters to the coarser dust.

Some electron microscope measurements on particulates in diesel exhaust are included. It is shown that the primary particles are spherical, about 0.05 μm in diameter, and that these exist as single particles, agglomerates and clumps of agglomerates. It is suggested that the diesel exhaust particulates form the major part of the airborne dust in the 0.03- to 1-μm size range in mines with diesel-powered equipment.

INTRODUCTION

The size distribution of aerosols in mine air is important because it affects directly the deposition of dust particles in the lung and affects indirectly the behavior of radon and thoron daughters, both in losses to mine walls and site of deposition in the lung. This chapter concerns the size distribution of aerosols in the range controlled by inertial effects, i.e., above 0.5 μm and with diesel exhaust particulates by electron microscopy. Some work in this area has been described previously [Knight 1972].

INSTRUMENTATION AND TECHNIQUES

Most of the size measurements were carried out with a set of size-selective samplers with mid-cut sizes ranging 1.25–7.1 μm. These samplers are optimized for collection of dust passing the size selectors on backup filters with subsequent assessment by weighing and XRD directly on the filter. Seven of the size selective samplers used horizontal elutriators as the first stage; their size selection characteristics were calculated from theory [Walton 1954]. Two impaction size selectors were built following theory [Mercer et al. 1970], neglecting the slip factor term, with mid-cuts in the 1- to 2-μm size range. However, it was found that these single-stage impactors were overloaded and extra, successively coarser, stages were added preceding the desired stage to increase the dust-holding capacity. In the final sampler it was found that there was no visible evidence of deposition (apart from the cones under the orifices) on the last two impaction stages when >1 mg of dust was collected on the final filter. The 5-liter/min impactor has six impaction stages and the 10-liter/min impactor has eight. These were then calibrated against horizontal elutriators in a mineral airborne dust cloud prepared by comminution to give an equivalent mid-cut size. An open filter was also used. The set of samplers is described in Table I.

The dust collected on the final stage filter in the size selective samplers was assessed to give four assessments of dust:

1. Total size-selected dust was determined by weighing before and after sampling.
2. Size-selected combustible dust or its corollary ash normally is determined as loss of weight on ashing at 500°C. However, in these experiments most of the dust samples were too light for accurate determination. In the blasting experiments the filter material was heavily stained and suffered a weight loss on ashing. Combustible dust was estimated for some runs by assuming that the mineral airborne dust is 50% quartz, as has been found on average in these mines for respirable dust.
3. Size-selected quartz dust was determined by XRD [Knight 1978].
4. Alpha-particle count was determined with a scintillation counter about four hours after the end of the 2- to 8-hr sampling period. The α count would

Table I. Size-Selective Sampler Characteristics

Sampler	Airflow (liter/min)	Mid-cut Size (μm)
Open	1	a
Elutriator 1	1	7.1
2[b]	1	5.0
3[b]	1	5.0
4	1.4	4.1
5	2.0	3.5
6	2.8	3.0
7	4.0	2.5
Impactor 1	5.0	2.1[c]
2	10.0	1.42[c]

[a] Total dust, but some loss of coarse dust due to mounting position, nonisokinetic sampling, etc.
[b] British Medical Research Council respirable dust specification run in duplicate.
[c] Equivalent mid-cut size determined by comparison with horizontal elutriators.

> then be due mainly to decay of thoron daughter ThC. Because of uncertainty of the time and the composition of radiation as collected, no attempt was made to derive airborne dust concentrations. The results are expected to be a reasonable estimate of the size distribution of the aerosol associated with radon and thoron daughters.

One stope was selected at each of three uranium mines where the airflow, both quantity and quality, was largely unaffected by other mining operations. The set of size-distribution samplers was operated for 2–8 hr in the return air from the stope while a particular mining operation was in progress. Other dust, radiation and ventilation measurements were made at this point, as well as in the intake air to the stope during the same period; these results are given elsewhere. The estimates of respirable dust production obtained during the mining operations have been published [Knight 1980].

The first stope was in a steeply inclined area, and there were three mining operations examined during the experimental period:

1. jackleg drilling a slash;
2. slushing using an electric winch; and
3. blasting a slash.

The return air dust measurements were made about 30 m along a 1.5- × 2-m return raise. The airflow through the stope and raise was about 2 m^3/sec. The second stope was in a flat area, and the three operations sampled were a 5-ton scooptram cleaning up the face ready for drilling; blasting a slash; and an 8-ton scooptram loading at the face with part of its haulage cycle. The return air dust measurements were made about 60 m back from the blind face of the stope in a 25- × 10-m opening. The 8-m^3/sec airflow near to the face was supplied through flexible ducting in good condition.

The third stope was in a steeply inclined area and the main operation was drilling with 2–4 down-the-hole drills (10 cm diameter). The return air dust measurements were made about 30 m downwind from the drills in a 20-m^3/sec airflow. The diesel exhaust particulates reaching the samplers were usually from a much greater distance.

Some electron microscopic studies of diesel exhaust particulates have been made. The engine was an air-cooled six-cylinder diesel commonly used in Canadian mines. The samples were taken at the diesel engine test facility in Ottawa under nine conditions: idle, half and full engine torque for each of low, intermediate and high speeds. The torques and speeds used are shown in Table VI. The samples were collected on Millipore filters (GSWP 04700) with a 0.22-μm pore size. Photomicrographs were prepared in the electron microscope and the particles were visually counted in size ranges.

Table II. Size Distribution of Total Dust

			Mass Undersize Expressed as Percentage of Respirable Size							
			Design 50% Size Cut[a] of Size Selectors (μm)							
Run	Operation	Open Filter	7.1	5.0	4.1	3.5	3.0	2.5	2.1	1.4
Site 1										
1	Slushing	128	114	100	86	70	76	53	49	41
2	Drilling	212	162	100	84	81	75	44	67	64
3	Drilling	185	150	100	97	80	82	29	60	62
4	Blasting	260	147	100	75	72	60	22	17	14
5	Drilling	200	150	100	113	92	83	53	66	14
Site 2										
6	Idle	150	200	100	75	50	36	12	30	30
7	Idle	200	100	100	75	100	71	50	40	70
8	ST5 Scraping	120	133	100	51	40	83	90	80	85
9	Blasting	83	91	100	82	69	66	57[b]	42[b]	[b]
10	ST8 load haul		100	100	88	83	89	85	85	
Site 3										
11	Drilling[c]	366	132	100	79	70	66	61	58	32
12	Drilling[c]	560	153	100	100	76	71	64	65	66
13	Drilling[c]	490	171	100	81	77	61	64	61	64
14	Drilling[c]	320	125	100	87	83	77	75	75	77

[a] The design cut size of the horizontal elutriators used.

[b] These filters developed heavy stains during blasting and the weights are suspect.

[c] Down the hole drill.

EXPERIMENTAL RESULTS

The results obtained using the set of size-selective samplers and the four assessment methods are given in Tables II to IV, with a summary in Table V and Figure 1.

The results in Table II show substantial variations due to the very low weight of dust collected, and a smooth size distribution cannot be shown for single runs. However, the overall means in Table V and Figure 1 show a reasonably smooth size distribution. Determination of quartz is more sensitive and less subject to error than total dust, and the size distributions for single samples are smoother.

Figure 1 shows that radiation has very little association with the dust collected by the size selectors and that the amount collected on the filters is constant. Individual runs show very wide variations in the normalized

Table III. Size Distribution of Airborne Dust: Quartz

Run	Operation	Open Filter	Mass Undersize Expressed as Percentage of Respirable Size							
			Design 50% Size Cut[a] of Size Selectors (μm)							
			7.1	5.0	4.1	3.5	3.0	2.5	2.1	1.4
Site 1										
1	Slushing	71	143	100	70	45	62	22	36	27
2	Drilling	229	153	100	80	62	52	22	31	28
3	Drilling	189	330	100	96	63	98	47	60	63
4	Blasting	188	141	100	72	63	53	21	14	13
5	Drilling	168	71	100	93	75	61	44	40	27
Site 2										
6	Idle	122	74	100	85	60	38	40	29	6
7	Idle	255	336	100	77	86	52	73	48	59
8	ST5 scraping	204	102	100	62	47	47	58	66	67
9	Blasting	138	114	100	70	71	80	73	46	
10	ST8 load haul		199	100	138	86	33	53	41	19
Site 3										
11	Drilling[b]	660[c]	178	100	80	63	57	39	25	11
12	Drilling[b]	650[c]	214	100	114	50	49	43	20	22
13	Drilling[b]	700[c]	146	100	73	48	43	32	16	14
14	Drilling[b]	420[c]	151	100	77	45	41	32	22	32

[a] The design cut size of the horizontal elutriators used.

[b] With a down the hole drill.

[c] There could be a substantial error in the x-ray diffraction calibration for quartz on such coarse dust.

Table IV. Size Distribution of Airborne Dust Associated with Daughters

		Count Undersize Expressed as Percentage of Respirable Size								
			Design 50% Size Cut of Size Selectors (μm)							
Run	Operation	Open Filter	7.1	5.0	4.1	3.5	3.0	2.5	2.1	1.4
Site 1										
1	Slushing	81	119	100	98	86	72	44	58	69
2	Drilling	121	124	100	126	123	97	68	97	123
3	Drilling	73	112	100	160	79	73	47	71	76
4	Blasting	70	112	100	97	132	115	71	65	110
5	Drilling	100						61	61	70
Site 2										
6	Idle	98	200	100	63	42	25	17	36	33
7	Idle	163	116	100	92	110	79	68	71	45
8	ST5 scraping	133	118	100	56	79	105	131	140	145
9	Blasting	63	96	100	84	86	77	77	96	106
10	ST8 load haul	97	79	100	98	88	129	155	175	227
Site 3										
11	Drilling	95	106	100	100	112	102	122		
12	Drilling	89	95	100	67	90	89	85	75	135
13	Drilling	126	110	100	109	92	92	120	115	163
14	Drilling	96	83	100	121	99	81	142	143	184

count rate (proportional counts on filter/minute per liter/min sampling airflow for each run). Presumably the large variations are due to three main factors:

1. The very low count rate—total of counts on each filter ranged 25–400 for most filters with one run at about 2000 per 9 min.
2. The 5-μm pore size silver membrane filters were unsuitable for radiation (they were chosen for the quartz analysis).
3. Variable losses of unattached daughters occurred by diffusion in the size selectors; however, as the measured unattached daughter ratio was less than 5% the loss was probably trivial.

DIESEL EXHAUST ANALYSIS

Size

The results of the electron microscope counting are shown in Table VI, and the mass undersize is shown in Figure 2. It can be seen that most of the

Table V. Summary of Size Distributions

		Mass Undersize Expressed as Percentage of Respirable Size							
		Design 50% Size Cut of Size Selectors (μm)							
Operation	**Open Filter**	**7.1**	**5.0**	**4.1**	**3.5**	**3.0**	**2.5**	**2.1**	**1.4**
Total Dust									
Slushing	120	114	100	86	70	76	53	49	41
Scooptram	120	116	100	70	61	86	87	82	85
JL Drilling	200	154	100	91	82	73	40	50	31
DH Drilling	435	145	100	87	76	69	66	65	60
Blasting	171	119	100	78	70	63			
Mean[a]	240	140	100	84	76	71	54	58	53
Quartz									
Slushing	71	143	100	70	43	62	22	36	27
Scooptram	204	150	100	100	66	40	55	53	43
JL Drilling	193	185	100	90	67	70	38	44	39
DH Drilling	607[b]	172	100	86	51	47	36	21	20
Blasting	163	127	100	71	67	66	47	30	
Mean[a]	307	181	100	85	79	55	43	35	30
Radiation Count[c]									
Slushing	81	119	100	98	86	72	44	58	69
Scooptram	115	99	100	77	83	117	143	157	186
JL Drilling	97	118	100	143	101	85	57	84	100
DH Drilling	101	99	100	99	98	91	117	111	161
Blasting	66	104	100	90	109	96	74	80	108
Mean[a]	100	13	100	98	94	87	86	100	113
Nonmineral Dust[d]									
Scooptram		100	100	44	60	100	100	100	
JL Drilling	190	150	100	98	79	85	51	69	50
DH Drilling	340[e]	129	100	88	91	81	86	90	84

[a] Arithmetic mean of individual runs in all mines.

[b] Probably low because of inaccurate X-ray calibration for such a coarse dust.

[c] Alpha count a few hours after sampling.

[d] Nonmineral dust calculated from total dust mass minus twice the quartz dust mass (airborne mineral dust contains 40–60% quartz in this area).

[e] Probably high, see footnote b above.

particles present on all specimens were below 0.5 μm in size. While the large-particles contribution is evident in Figure 2, at least 75% of the total particulate weight was below 2 μm, with the exception of the 1600-rpm full torque point (curve F, Figure 2). The difference between the 1600-rpm full torque point and the rest of the test series casts some doubt on the validity

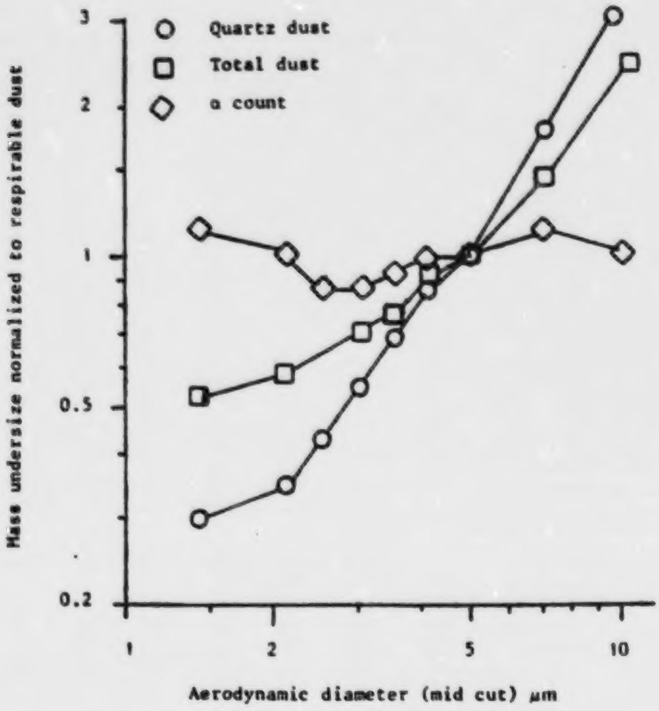


Figure 1. Mean size distributions as assessed by weight (total), X-ray diffraction (quartz) and alpha count (thoron daughters).

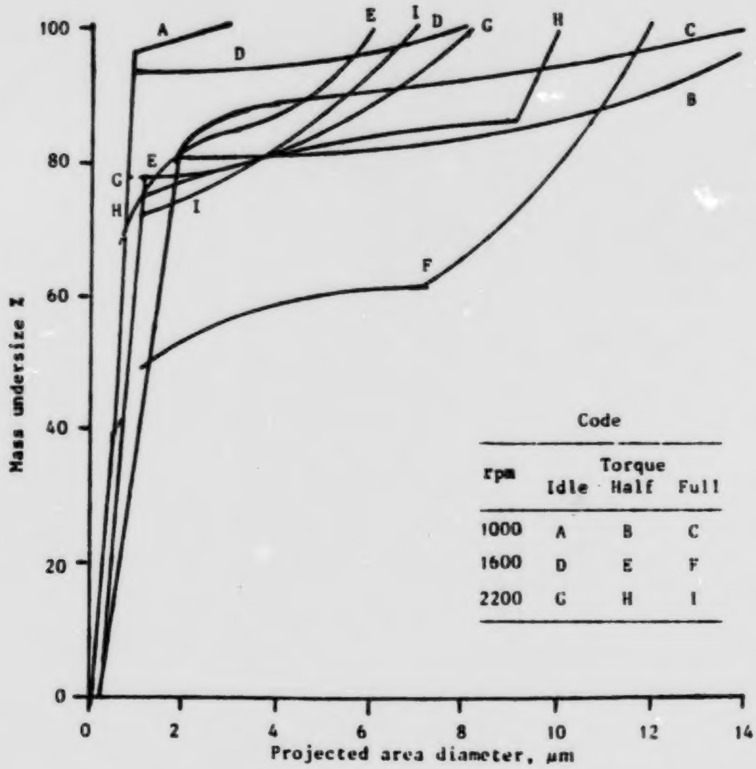
of the sample. However, a check, provided by a 1800-rpm full torque point, agreed with the 1600-rpm point. Therefore, it was concluded that the mechanical configuration of the engine preferentially increased the number of large particles found in the exhaust stream at intermediate speed and high load.

A general tendency was observed toward increased maximum particle size with decreased speed. A lack of significant numbers of large particles at low and intermediate speed idle was also apparent (curves A and D; Figure 2). Clogging of the pore structure, probably with liquid hydrocarbon (either altered fuel or heavy ends present in the fuel) was detected at low-speed idle.

Table VI. Diesel Exhaust Particulate Size Distribution Counts on Electron Miscroscope Photographs

Speed (rpm)	Torque (N-m)	Size (μm)																
		14–15	13–14	12–13	11–12	10–11	9–10	8–9	7–8	6–7	5–6	4–5	3–4	2–3	1–2	0.5–1.0	0.15–0.5	0.05–0.25[a]
1,000	0													1	6	1,218	6,000	12,400
1,000	205	1	1	1	1	1	2	1	2	2	3	5	7	12	10,010	50,000	120,000	240,000
1,000	410		1	1			1	3	3	2	4	8	100	100	10,200	91,500	90,000	220,000
1,600	0								1	1	3	1	1	1	13	20,031	160,000	730,000
1,600	190										1	1	1	4	61	512	27,200	64,000
1,600	380				1		1	1	1			1	7	10	144	6,864	19,200	99,200
2,200	0								1	1	1	2	2	3	35	6,400	30,400	65,600
2,200	175						1				1	1	4	2	52	8,256	17,600	57,600
2,200	350									1	3	3	6	13	74	4,000	51,200	72,000

[a]Smallest particles on the filter were 0.05 μm in diameter.



Code

rpm	Torque		
	Idle	Half	Full
1000	A	B	C
1600	D	E	F
2200	G	H	I

Figure 2. Diesel engine exhaust particulates: size distribution.

Particle Structure

The physical appearance of all sizes of particles remained consistent throughout the load-speed range tested. The smallest particles found on the specimens were 0.05 µm in diameter. While the resolution of the electron microscope prevented detailed analysis of the smallest particles, they appeared "monolithic" in the 500,000X photo. Only rarely were these particles isolated; in most cases they were agglomerated in random popcorn-shaped clusters. All agglomerates of 1 µm and smaller were tightly clustered groups of small (0.05-µm) particles.

The larger agglomerates appeared to be much more porous and resembled loosely joined groups of the smaller, more compact, agglomerates. Because of shape and density the aerodynamic size would be substantially less and collection in the size selectors could be much less than suggested by the projected area diameter used in Figure 2.

It is probable that the smallest particles (0.05 μm in diameter) are the building blocks from which all the diesel agglomerates are formed. As the number of building blocks in the particle increases there is a tendency for the particle to become rounded and more porous.

DISCUSSION

The results obtained for airborne quartz dust show that the mass undersize approximates to a power law truncated at the top end by settling. This distribution is close to earlier work and to the theory of rock breakage [Hamilton 1959], followed by gravitational settling in the airway as expected from the theory given by Walton [1954].

The results for total dust show a flatter line than do results for quartz. This is particularly marked for the two operations (runs 8 and 10) where diesel-powered vehicles were used. The calculated values for nonmineral dust (Table V) on these two runs suggest that very little of the nonmineral dust is coarser than 2 μm. Presumably, most of this is particulates from the diesel engine exhaust; this confirms the conclusion of the laboratory studies "that most particles by number are less than 0.5 μm in diameter and between 50 and 95% of the total particulate weight (calculated from projected area assuming uniform density and shape throughout the size range) is less than 2 μm, in size."

Only a very small proportion of the radon and thoron daughters are associated with the coarser airborne dust that was removed by these selectors. That is, most of the attached daughters are associated with particles less than 1 μm in size.

A few measurements were made in this study with a small particle detector (type CN, Gardner Associates Inc.) at its No. 5 setting (lower limit approximately 0.001 μm), suggesting that the count levels were about 3×10^5 particles per cm^3.

Figure 3 shows what might be expected as average size distributions by number, diameter, projected area and mass. This figure has been derived by adding three types of dust:

1. Mineral dust concentration assumed is 0.2 mg/m^3, as the highest average concentration found for extended periods of many shifts at any working place. Assumed distribution by number increased by a factor of eight for every halving in size down to an arbitrary lower size limit of 0.25 μm.
2. Diesel exhaust particulates concentration assumed is 1.0 mg/m^3 from the average measurement in diesel areas of the mines. Size distribution was taken

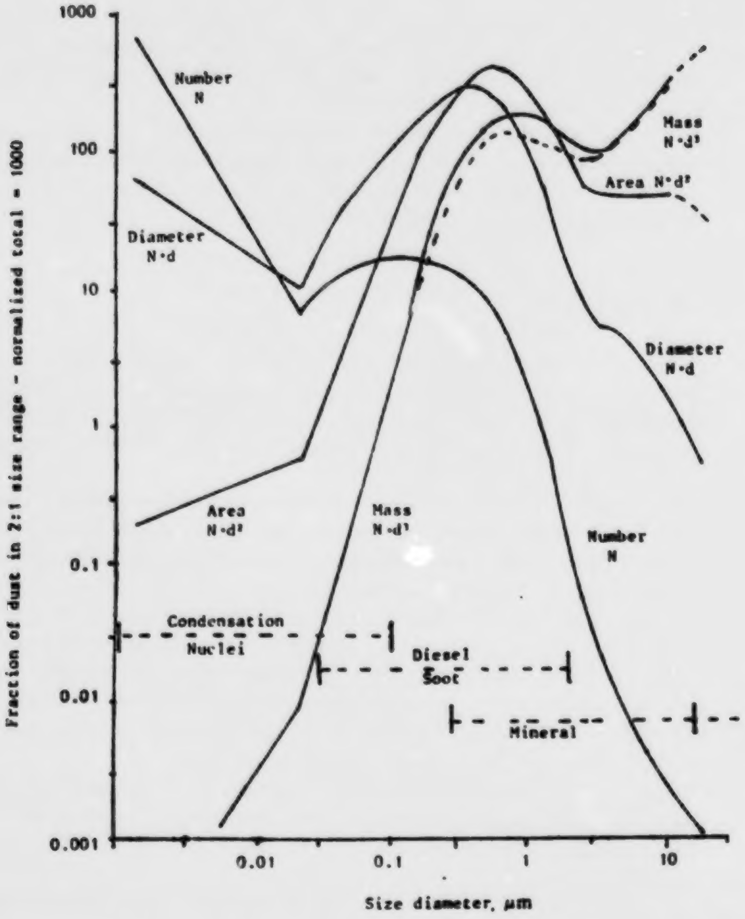


Figure 3. Calculated size distributions as assessed by number N, diameter N·d, area N·d^2 or mass N·d^3 based on simple assumptions.

from Table VI. Also shown as a dotted line for mass only is the effect of an allowance for low density of agglomerates as compared to mineral and a change to aerodynamic size for the allomerates above 1 μm in projected area size.

3. Condensation nuclei are included as a smooth curve ranging from 100 at above 0.01 μm to 3 × 10^5 above 0.0015 μm.

It is also assumed that shape and density are the same for all constituents. While obviously not true (these assumptions are rough), it is believed that the overall picture is reasonable and shows that condensation nuclei are only the major contributor to number but that they are hardly significant in N·d and not at all in area and mass. Diesel soot is the main contributor to N·d and area. Mineral dust and nonsoot diesel particulates are the main contributors to mass.

Clearly, far more data are needed to enable accurate calculations of number, N·d, area and mass, particularly in the size region of diesel soot, and to enable reasonable predictions of the size distributions of particles associated with radiation. The results obtained do not permit any conclusions other than that daughters are not associated with particles as assessed by mass.

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Section 4 - Chapter 27

Size Distribution of Airborne Dust in Labrador Iron Mines

by

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DISTRIBUTION GRANULOMÉTRIQUE DES POUSSIÈRES EN SUSPENSION DANS L'AIR DANS LES MINES DE FER DU LABRADOR

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La distribution granulométrique de la poussière totale en suspension dans l'air et de ses composantes s'approche d'une ligne droite sur un graphique du log du passé en masse en fonction du log de la taille aérodynamique. La distribution de la composante quartz a une pente assez constante, est voisine des distributions obtenues dans d'autres mines et concentrateurs, et obéit aux lois de fragmentation normales. Les résultats obtenus pour la composante fer portent à croire que la fraction supérieure présente est similaire à celle du quartz et que la pente est aussi similaire. Les pentes obtenues pour la poussière totale en poids ne sont pas aussi fortes que pour le quartz, ce qui porte à croire qu'il y a une distribution bimodale consistant en la combinaison d'une fraction minérale grossière et d'une fraction plus fine provenant d'autres sources, par exemple produits de combustion, qui sont souvent présents. Les pentes obtenues pour le manganèse sont parfois beaucoup plus faibles que pour le fer ou le quartz, ce qui porte à croire que le manganèse est associé à une roche plus apte au concassage. Le seul résultat obtenu pour le chrome porte à croire qu'il est associé principalement à de très fines particules et, par conséquent, peut avoir été dispersé sous forme de fumées à la suite d'une opération tel le soudage.

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Size Distribution of Airborne Dust in Labrador Iron Mines

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The size distribution of the total airborne dust and its components approximates a straight line on a plot of log mass undersize against log aerodynamic size. The quartz component distribution has a reasonably constant slope, is close to the distributions found in other mines and mills, and follows the normal breakage laws. The results for the iron component suggest that the top size present is similar to that of quartz and that the slope is also similar. The slopes for total dust by weight are not as steep as for quartz and suggest a bimodal distribution consisting of a coarser mineral fraction mixed with a finer fraction from other sources, such as combustion products, that are often found. The slopes for manganese are sometimes much less than for iron or quartz and suggest that manganese is associated with a more crushable rock. The one finding of chromium suggests that it is associated mostly with very fine particles and, therefore, may have been dispersed as fume from an operation such as welding.

Introduction

During the course of a major dust study at the Labrador Iron Ore Mines, a limited number of tests were carried out to measure the size distribution and composition of the airborne dust typical of the various stages of ore processing in the two mills.

This report is limited to the size distribution of the total airborne dust and some of its constituents.

Experimental Methods

The Elliot Lake Laboratory in its characterization of airborne dust has concentrated on the mineral portion in the respirable size fraction, as the major objective is to reduce lung diseases such as silicosis. To this end, the laboratory has developed a set of two-stage dust samplers with 50% size cuts ranging from 1.4 to 7.1 mm.[1-4] The second stage of these samplers is a filter collecting all the undersize dust in a form suitable for direct X-ray diffraction analysis for crystalline minerals with the use of the techniques developed for quartz on gravimetric samples.[4,5] An open-face filter also is used.

The first stage of the coarser four of these samplers consisted of horizontal elutriators. That of the four finer samplers consisted of impactors; these were multistage to increase their dust-holding capacity without overloading the final stage, since overloading can result in changes in size selection characteristics.

Multistage impactors have been designed previously in the laboratory following the published work;[7] however, a minor disagreement between expected and tested performance has been found, presumably because of interstage losses, *etc.* To maintain a uniform definition of size throughout the range, an equivalent 50% horizontal elutriator cut has been determined for each impactor size selector by comparison with horizontal elutriators in a comminuted polydisperse coal dust cloud.[3] The expected impactor size selection is about 10% less in diameter than the equivalent horizontal elutriator 50% cut. The determination of the parameters of an assumed log normal size distribution dust cloud from measurements with horizontal elutriators has been given previously.[1]

The size-selective sampler meeting the British Medical Research Council (BMRC) respirable dust selection criterion is run in duplicate and is used to define the "respirable dust component." Thus, a total of seven two-stage samplers is shown on the graphs.

The airflows used are 1 L/min for the four coarser sized samplers and are increased, up to 10 L/min, for the others so as to obtain approximately the same weight of dust on the finer sized selective samplers as on the duplicate respirable dust samplers.

The dust samples, collected on 25 mm diameter silver membrane filters, were assessed by:

1) weighing to give total dust on each sized fraction;
2) X-ray diffraction to give quartz dust on each sized fraction;[5]
3) X-ray fluorescence to give elemental composition on a few selected filters.[6]

The sites selected for sample collection were:

Mine 1

1) crushed ore storage, as typical of raw ore;
2) milled ore storage, as typical of milled ore, feed to classifiers;
3) balling mill area, as typical of beneficiated ore;
4) pellet screen house, as typical of indurated pellets;

Mine 2

5) a) classifier area (concentration too low, one run) replaced by:
   b) crushed ore storage, as typical of raw ore:

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6) cleaner spiral floor, as typical of first stage beneficiated ore;
7) high tension area, as typical of highly beneficiated ore;
8) Jones circuit area, as typical of this specific operation.

Four to six tests were carried out at each of these test sites. A single test was carried out also in each of six other areas of special interest for exposure reasons. These areas had either a high concentration or a particularly low concentration, the latter selected as working places suitable for individuals showing early signs of pneumoconiosis.

Results

Table I shows a summary of the mass collected and the concentrations in the selected areas. Calibration for XRD analysis was carried out. Collections were made with the size distribution sampling train, and dust from a pure quartz dust cloud was weighed.[5] This procedure corrects for the differences in particle size and area distribution between the various samplers.

Mass median aerodynamic diameters have been derived from the open filter, the coarsest elutriator sampler and the duplicate respirable dust samplers with the use of the tech-

TABLE I
Summary of Main Experiments Showing Masses Collected and Concentrations of Respirable Dust and the Measured Components

Site No. Description	Sampling Time min	Respirable Dust Mass[A]		Respirable Dust Conc.	Respirable Quartz Mass[A]			Respirable Quartz Conc.	Respirable Iron as Fe		Respirable Manganese as Mn		Chromium as Cr	
		mg	mg	mg/m^3	µg		%	mg/m^3	%	mg/m^3	%	mg/m^3	%	mg/m^3
1214140	322	0.13	0.13	0.40	13	13	10	0.04	20	0.08	1	0.0	0	
Crushed Ore	401	0.17	0.16	0.41	12	8	4	0.025						
Storage	412	0.33	0.31	0.78	78	80	24	0.19						
	402	0.25	0.23	0.60	51	47	20	0.12	25	0.15	2	0.01	0	
	1430	1.01	-[B]	0.71	295	-	29	0.21	28	0.20	1.2	0.01	0	
1251149	397	0.14	0.14	0.35	20	16	14	0.05	18	0.07	2	0.01	0	
Milled Ore	391	0.23	0.23	0.59	34	33	15	0.09	27	0.16	1	0.01	0	
Storage	400	0.17	0.16	0.41	33	14	14	0.06						
	425	0.25	0.19	0.52	16	26	10	0.05						
	1560	1.71	1.60	1.06	321	368	21	0.22	29	0.31	3	0.03	0	
1321110	370	1.29	1.73	4.10	10	10	1	0.02	13	0.54	0		0	
Pellet Balling	409	0.28	0.27	0.67	4	9								
Floor	407	0.24	0.28	0.64	2	2								
	392	0.47	0.30	0.98	11	10			27	0.26	0		0	
1361357	388	1.41	1.29	3.50	33	30	2	0.08	66	2.3	T	0.007	0	
Finished	375	1.13	1.05	2.91	31	42	3	0.10						
Pellets Screen	426	1.54	1.42	3.48	48	44	3	0.11	60	2.1	0		0	
	416	1.79	1.72	4.25	45	52	3	0.12	52	2.25	0		0	
2212206	420	0.08	0.07	0.20	7	5	5	0.01						
2213107	420	0.17	0.12	0.34	15	25	15	0.05	34	0.12	9	0.03	0	
Crushed Ore	382	0.19	0.19	0.50	11	7	4	0.02						
Storage	413	0.13	0.09	0.27	113	64	80	0.22	21	0.06	3	0.01	0	
	1415	0.39	0.33	0.27	50	41	11	0.03	35	0.09	6	0.02	0	
2231112	382	0.25	0.26	0.67	7	5	2	0.02	85	0.57	1	0.01	0	
Spirals	408	0.14	0.14	0.34	6	7	5	0.02						
Area	411	0.25	-	0.61	3	-	1	0.01						
	383	0.23	0.23	0.60	75	37	25	0.15	38	0.23	5	0.03	3	0.02
	406	-	0.36	0.89	-	9	2	0.02						
	1535	0.44	0.41	0.27	18	21	4	0.01						
2232318	388	0.03	0.03	0.08	20	5	2	0.01	40	0.03	7	0.01	0	
Jones	372	0.25	0.22	0.63	8	0								
Dryer	428	0.38	0.30	0.77	10	8			34	0.26	6	0.04	0	
	1405	0.80	0.80	0.57	11	20								
2233321	418	0.23	0.21	0.52	4	6	2	0.01	33	0.17	1	0.005	0	
High Tension	414	0.20	0.19	0.46	10	8								
Area	417	0.43	0.43	1.03	10	6								
	416	0.20	0.19	0.47	6	6								
	1425	0.58	0.54	0.39	11	9			50	0.20	7	0.03	0	

[A] Duplicate results are entered for mass, mean for % and concentration.
[B] Sample lost.

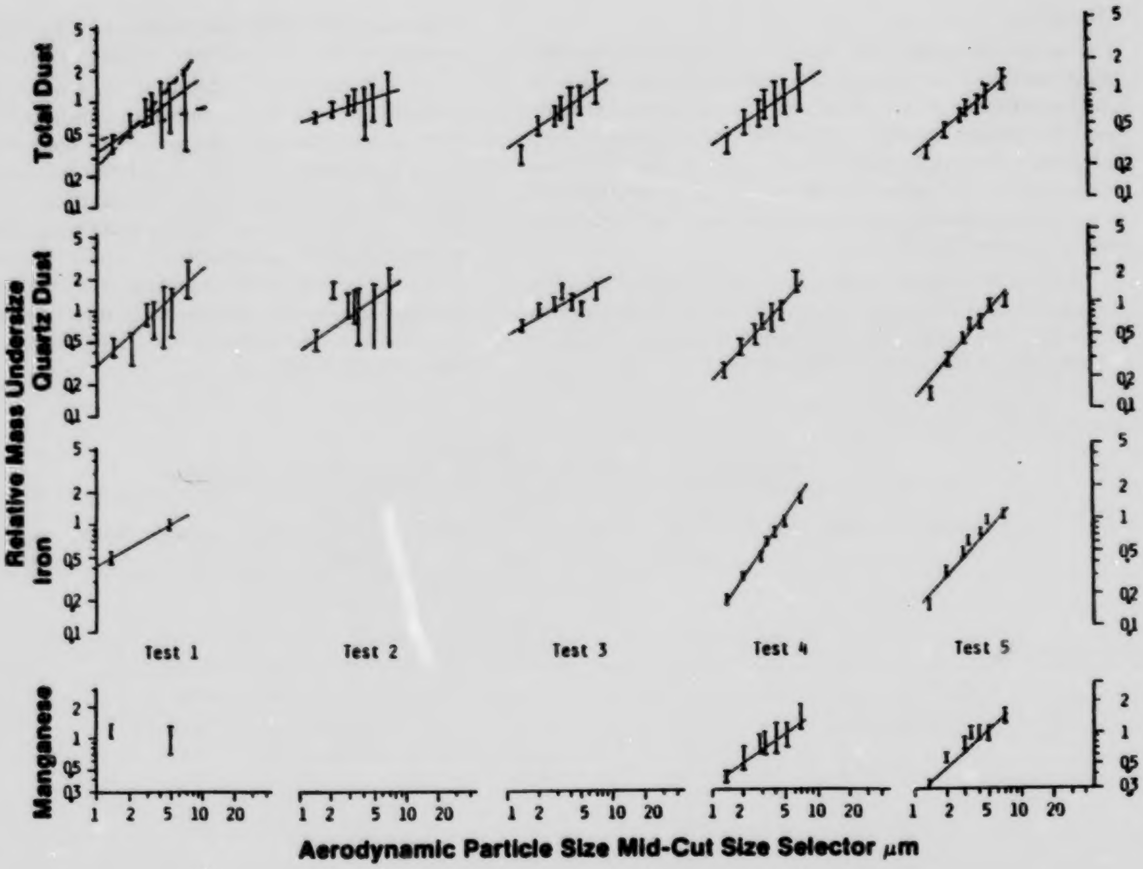

Figure 1 — Size distribution plots: crushed ore — site 1214140.

niques given in a previous paper.[1] When the indicated MMD was less than 5 μm, the result was re-evaluated with the open filter, the duplicate respirable dust samplers and the finest elutriator sampler. Whereas this technique also gave the slope of the assumed log normal dust size distribution with seven size selections and the open filter, a lot of slopes would be obtained and an alternative approach was used: to plot the results of log mass undersize (strictly the dust passing the sampler) against log size (the 50% size cut of the elutriator). The error bars on the graph for total and quartz dusts are derived from the experimentally determined differences between duplicate respirable dust samples collected in other programs in the mines. In these it was shown that 95% of the pairs of samples have differences less than:

± 0.1 mg ± 0.1 $\overline{W}$ for dust by weight where $\overline{W}$ is the mean weight of the pair of samples;

± 0.01 mg ± 0.1 $\overline{Q}$ for quartz dust where $\overline{Q}$ is mean quartz.

For iron, manganese and chromium the error bars are determined from the square root error of the count and a 10% error as above for sampling effects.

Having drawn the graphs, one determines the slope by drawing a pair of lines within the error bars with maximum and minimum slopes, respectively. The most probable slope is obtained when this pair of lines is bisected, as shown in the upper left corner of Figure 1. Figure 1 shows all the plots for site 1 as an example. The vertical scale is normalized so that the respirable dust is at the unit value. Note that tests 1 and 2 gave rather indefinite lines. Tests 3, 4 and, particularly, 5 gave more closely defined lines because of the greater weights of dust collected on the filters. The size distribution data are given in Table II. The omission of a result, represented by –, signifies that the result was too indefinite because of wide error bars due to low sample weight.

The results of the tests in special areas are summarized in Table III.

The slope is given as the exponent for the power law (straight line on a log-log plot) in the expression:

$$MU = kP^s$$

where MU is mass undersize;
k is a constant;
P is aerodynamic size; and
s is the exponent or slope.

The test in which chromium was detectable suggested that most of it was fine; possibly it could have been dispersed during welding.

Discussion

The results obtained show that a straight line on the log-mass-undersize log-size plot is a reasonable description of the size distributions as measured. For the quartz component the slopes of about 1.2, found on the samples with adequate amounts for analysis, are in reasonable agreement with previous studies in other mines(4) using this method and with microscopic techniques used elsewhere, as well as with the theory developed.(8)

For the total dust by weight the slopes tend to be less than for quartz, particularly at low concentrations. Probably this tendency is caused by non-mineral dust from sources such as combustion processes that characteristically consist of particles mostly less than 1 μm in size and thus form a constant concentration on all the filters in this size distribution train.

X-ray fluorescence analysis showed only two elements (above silicon in atomic number) in significant quantities on most filters, iron and manganese. In one run substantial amounts of chromium were found; this was mostly fine and was likely to have been dispersed by a special operation such as welding. That the iron usually had a steep slope similar to quartz suggests it was following a similar breakage pattern. The lower average slope for manganese could be due to the manganese minerals' being more friable than quartz or iron, or possibly to an experimental error associated with the lesser quantities found.

TABLE II
Size Distribution Data Mass Median Diameter (MMD) and Slopes

Site	Test	MMD	Total Dust Slope	MMD	Quartz Dust Slope	MMD	Iron Ore as Fe Slope	MMD	as Mn Slope	MMD	as Cr Slope
1214140	1	6.0	0.7	5.5	0.94	5.5	0.56				
	2	2.0	0.32	7.5	0.66						
	3	6.5	0.68	11.0	0.56						
	4	9.6	0.64	5.2	1.12	7.5	1.5	4.5	0.68		
	5	3.8	0.84	5.0	1.18	4.0	1.12	4.0	0.98		
1251149	1	5.5	0.5	5.0	0.76	3.0	0.44	-	0.18		
	2	4.5	0.8	5.0	1.16	4.5	0.88	2.8	0.42		
	3	9.0	0.56	7.5	0.98						
	4	4.8	0.54	-	-						
	5	5.2	0.5	-	0.42	5.5	0.54	2.0	0.22		
1321110	1	4.5	1.86	6.5	1.40	7.0	1.46		-		
	2	7.5	0.86	-	-						
	3	6.5	0.88	-	-						
	4	7.2	1.24	-	-	5.5	1.2		-		
1361357	1	-	1.96	-	1.74						
	2	8.0	1.62	-	1.54	5.0	2.2	3.0	1.14		
	3	6.5	1.52	6.0	1.4	-	2.36	-	-		
	4	8.0	2.1	-	2.06	-	2.1	-	-		
2212206	1	5.5	1.46	7.0	2.3						
2213107	1	7.5	0.76	-	-	6.0	0.96	4.0	0.8		
	2	-	0.2	11.0	0.8						
	3	-	0.72	-	2.2	4.5	0.74	-	0.56		
	4	6.3	0.74	-	1.1	3.0	0.6	2.8	0.54		
2231112	1	3.5	0.96	-	1.36	-	0.9	-	0.36		
	2	2.2	0.24	-	0.78						
	3	-	0.26	-	0.2						
	4	1.0	0.3	-	2.2	2.0	0.4	-	0.0	<1	0
	5	2.5	0.36	-	-						
	6	1.5	0.24	7.0	1.06						
2232318	2	-	0.78	-	-						
	3	-	1.1	-	1.3	7.0	1.16	6.5	1.0		
	4	10.0	1.1	-	-						
2233321	1	-	0.82	-	1.22	-	0.9	-	0.0		
	2	10.0	0.82	-	-						
	3	-	1.36	4.8	1.2						
	4	8.5	0.7	6.0	1.5						
	5	9.0	0.64	12.0	1.06	4.0	1.06	4.0	0.76		
Mean		6.1	0.80	7.0	1.224	4.9	1.11	3.7	0.55	<1	
Standard Deviation			0.46		0.529		0.59		0.33		
Coeff. of Variation			58		43		53		60		

TABLE III
Summary of Results of Special Tests

Site # Description	Sampling Time/min	Respirable Dust mg/m^3	Respirable Dust MMD	Respirable Dust Slope	%	Respirable Quartz mg/m^3	Respirable Quartz MMD	Respirable Quartz Slope
1295185	New pump house top floor							
	1430	0.05	5	0.06	10	0.005	IQ	IQ^A
12513--^{B}	Chemistry laboratory grinding area							
	1450	0.48	5	0.45	16	0.08	6	0.95
129-----^{B}	Main warehouse							
	1430	0.07	7	0.4	10	0.007	IQ	IQ
1294184	Welding shop							
	1471	0.27	6	0.53	4	0.01	8.5	IQ
1294184^B	Small vehicle repair shop							
	1453	0.05	6	0.4	7	0.035	IQ	0.7
1251376	Steam plant center							
	1469	0.17	6	0.4	8	0.01	9	IQ

^{A}Insufficient quartz for determination of slope.

^{B}These three sites have not been fully defined in the numerical code used in routine dust sampling.

Simple statistics on the means and standard deviations of the slopes in Table II suggest that the differences between total dust or manganese and quartz or iron are statistically significant (probability level 0.05).

The mass median aerodynamic diameters showed large differences between different days at most of the sites. This variation is considered to be largely due to differences in coarse dust settlement. This variation also would be very large for operators, depending on their position. To determine the mass median diameter for workers' exposure would require personal sampling; however, in conjunction with the results presented here, it probably could be determined by a respirable dust sampler if both respirable and coarse dust (in the size selector) are assessed. From the worker exposure point of view, the ratio of the mass inhalable (or total) dust to that of respirable dust is a more useful concept than the mass median diameter. In this study the ratio ranged from 1.5 to 6 times for the quartz component.

It is also clear that the results approximate to a straight line on the log-log plots and that these would be better determined by more sampling at the end of the range and less in the middle. It is also apparent that the equal mass concept on each filter tends to give larger relative errors for the higher size samples than for the lower; thus, 2 L/min might be a better flow rate to use for these than 1 L/min. These considerations will be taken into account in adjusting the equipment for future use.

Acknowledgments

The author wishes to thank the staff of Environmental Survey Company (ESCO) for taking the samples and the Labrador Institute of Northern Studies for supporting the program.

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Section 5. Dust standards and Assessment Principles

5. 28

Section 5—Chapter 28

Size Selective Sampling

by

G. Knight

Occupational Health in Ontario 22(3) pp2-12 (1970)

Échantillonnage granulométrique sélectif

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Une analyse d'échantillonnages sélectifs de poussières atmosphériques et une description d'échantillonneurs granulométriques sélectifs sont présentées. Les poussières atmosphériques constituent un danger pour la santé du fait que, lorsqu'elles sont inhalées, elles peuvent causer diverses pneumoconioses (maladies pulmonaires).

Size Selective Sampling

by

G. Knight*

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ABSTRACT

Selective sampling of airborne dust is reviewed and size selective samplers are described. Airborne dust is a health hazard, if inhaled, in that it can cause various pneumoconioses (lung diseases).

Size Selection: Horizontal Elutriators: Cyclones: Respirable Dust: Pneumoconiosis

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INTRODUCTION

The dust sampling with which we are concerned is undertaken for the assessment and control of health hazards, particularly the pneumoconioses arising from dust deposited in the depths of the lungs, the alveolar region.

Clearly, dust can only be deposited in the alveolar region of the lungs after it has been carried through the bronchial passages. Dust particles are deposited from the air in both these regions by the processes of impaction, settlement and diffusion. The processes of impaction and settlement are important for the coarser particles above about 0.25 μm and diffusion is important below about 1.0 μm. These processes depend on the aerodynamic properties of the particles and it is useful to define the 'aerodynamic size' of a dust particle as the diameter of a unit-density sphere having the same falling speed in air as the particle in question. The falling speed of a dust particle depends on its size, density and shape.

The dependence of dust deposition in the lungs (1) on size is shown in Figure 1. This shows the range of variation that has been observed with breathing rate.

It is useful in understanding selective sampling to consider the history of dust sampling. At the start, the total amount of dust in the air was measured, as in the sugar-tube sampler (South African gold mines). The realisation of the large differences in dust size-distribution in the air and in the lungs led to the adoption of selective assessment, using a microscope, of samples collected by a variety of instruments, such as konimeters and impingers. Some of these microscope techniques are still in widespread use with a 5-μm-diameter upper size limit defining respirable dust. This limit is arbitrary (2) and came into use by common practise. It has the disadvantages that:

1. It does not accurately represent the respirable fraction and is density dependent.
2. The 5-μm particles are normally determined by examining them individually under a microscope; a tedious and inaccurate process.
3. It is impossible to use the same criterion to separate particles for compositional analysis.

These disadvantages led to consideration of aerodynamic-size selection to achieve more accurate representation of the dust deposited in the alveolar region and improve the design of dust-sampling instruments. This would permit better compositional analyses and an improved relationship between measurements of dust concentration and the health hazard in dust clouds differing in size distributions.

RECOMMENDATIONS FOR AERODYNAMIC-SIZE SELECTION OF RESPIRABLE DUST

Two-stage size selective samplers were proposed to simulate the two-stage deposition of dust in the bronchial passages and the alveolar region of the lungs. In the two-stage sampler, the first stage collects the dust that would deposit in the bronchial passages and the second, that in the alveolar region. For convenience, the efficiency of the second stage usually rises to a maximum of 100% instead of the 50% maximum deposition in the alveolar region of the lung (Figure 1).

Clearly, because of the variability of dust deposition in the lungs, a size selective sampler can only simulate an 'average' lung. There have been two approaches to this: firstly, the choice of a physically definable size selection system which is a reasonable approximation to the 'average' lung; and secondly, to define an 'average' lung size-selection and then find size selective devices which approach this.

The first approach, developed under the auspices of the United Kingdom Medical Research Council in 1950-52 (2), culminated in the recommendation (3) of the horizontal elutriator, a size selector with a simple theory (4) and demonstrated performance (5). The size selection is shown in Table 1.

The second approach, developed under the auspices of the United States Atomic Energy Commission Office of Safety and Health, resulted in 1961 in the specification of respirable dust (6) given in Table 1.

This specification was modified slightly by the American Conference of Government Industrial Hygienists (7) in 1968, and is also shown in Table 1. A number of authors have demonstrated that cyclone size selectors can give a good representation of this respirable-dust curve. However, the disagreement between the calibrations by these authors (6, 8, 9, 10, 11) - from 1.4 to 2.8 ℓ/min for one particular cyclone - shows the difficulties of the second approach.

Later theoretical work (12) has suggested that the differences between these two recommendations should amount to 15 to 30% in mass in the normal range of mine and industrial dusts. The ACGIH recommendation leads to the lower estimated respirable-dust concentration. This difference is small relative to the accuracy of dust sampling and the variation in lung characteristics.

SAMPLERS FITTED WITH SIZE SELECTORS

Respirable-dust samplers can be divided into classes by a number of factors:

1. type of size selector;
2. method of collection on second stage;
3. airflow rate.

The main classification used here is the first (type of size selector - horizontal elutriator, cyclone or other). Most current interest is in samplers in which the respirable dust is collected on a filter for gravimetric assessment or compositional analysis. These instruments can be separated into two classes; firstly, those which are readily portable, self-powered unit essentially with a low flow-rate and intended to operate for many hours; and secondly, those that require an external source of power and that operate at a high flow-rate intended to collect samples large enough for compositional analysis. With micro-analytical techniques, however, the samplers of low flow-rate may collect large enough samples.

1. Horizontal-Elutriator Size Selective Samplers

The recommendation to use two-stage respirable-dust samplers with horizontal-elutriator size selectors was made in 1952 (2). The horizontal-elutriator size selector has the great advantage that its performance can be determined by a simple theory of gravitational settlement (4), which was shown to be reasonably accurate as early as 1954 (13). To meet the Medical Research Council recommendations it is required that the flow is even over all the settlement area and that the ratio of flow to settlement area - $cm^3 min^{-1}/cm^2$ - is adjusted to a value of 9 cm/min, the settling velocity of a 7.1-μm unit-density sphere in air.

Following this recommendation many horizontal-elutriator size selectors were developed for a number of instruments then in use. The application to the thermal precipitator remains of current interest. The use of a size selector on the standard thermal-precipitator reduced overlap errors particularly in coarse dust-clouds, and led to the development of the Long-Period Dust Sampler (14), manufactured by Casella (M1). This instrument is self-contained, intrinsically safe, can sample - 2 cc/min - for a full shift, and can be assessed by optical microscopy or optical densitometry (15).

The Hexhlett dust-sampler was designed by Wright (13) in 1954 with a flow rate, controlled by a critical orifice (16), of 100 ℓ/min for collection of large quantities of respirable coal mine-dust for analysis. However, it was found that the dust settled out in the elutriator could, in some circumstances, be re-entrained by the high-velocity air between the plates and transferred to the second stage. This was stopped by removing half of the settlement plates, increasing the plate separation by 2.5 times and reducing the velocity correspondingly. The design flow-rate on this modified type is 50 ℓ/min and the respirable dust - second stage - can be collected on a soxhlett thimble or a GF/A glass-fibre filter disc, 5.5 cm in diameter. The Hexhlett, manufactured by Casella (M1), requires an external power-source, either a compressed-air operated ejector (supplied) or a vacuum pump (special order).

The NCB MRE gravimetric sampler was designed and tested at the National Coal Board Mining Research Establishment in England (17) and manufactured by Casella (M1). This instrument operates at 2.5 ℓ/min and is intended for long-period sampling (up to 10 hours). It is operated by a constant-volume diaphragm pump powered by a governed, intrinsically safe motor with a rechargeable dry-cell. The respirable dust is collected on an aluminum-mounted glass-fibre disc of 5.5-cm diameter, and up to 100 mg can be collected.

Some precautions have to be taken in use with these types of samplers:

1. Entry conditions - the NCB MRE gravimetric sampler can be used either facing upwind or crosswind, but not downwind, in air velocities up to 1200 ft/min (17). The

entry slots were added to reduce swirl inside the elutriator channels and extend the range of satisfactory operation. The same experiments have not been carried out for the Hexhlett, but without inlet slots it is probably satisfactory at velocities of up to 800 ft/min.

2. Airflow - the performance of the size selector alters appreciably with airflow and the 'respirable' mass collected changes by more than the error in flow rate. Reasonable care in maintenance of flow rate, avoidance of leaks and absence of visible damage to the elutriator should ensure adequate performance.
3. Handling care - rough handling can transfer settled dust from the elutriator to the second-stage collector. However, during normal handling, the chamber between the elutriator and the critical orifice in the Hexhlett or the turned-up ends of the settlement plates in the NCB MRE, will trap settled dust and thus prevent contamination of the respirable-dust sample.
4. Mounting - horizontal elutriators must be operated within 10 degrees of the horizontal and are therefore difficult to use as breathing-zone - personal - samplers.

2. Cyclone Size Selectors

Cyclone size selectors have the following advantages and disadvantages in comparison with horizontal-elutriator size selectors.

The advantages are:

1. For equal flows the cyclone is smaller.
2. The cyclone is much less sensitive to orientation.
3. Because of 1 and 2, respirable-dust samplers fitted with cyclone size-selectors can be used as personal samplers, mounted on a man and measuring the dust levels in his breathing zone.
4. The shape of the size selection curve is closer to the 'average' lung deposition than is that of the horizontal elutriator.
5. The mass collected on the second stage is not, in many dust clouds, affected by the flow rate as shown in Figure 3, and thus errors in sampling flow rate are not as important as in the horizontal elutriator. However, the calibrated flow rate rather than the actual should be used to determine the dust concentration.

The disadvantages are:

1. The size selection performance is not calculated with a sufficient accuracy and each cyclone size selector has to be calibrated to determine the most suitable flow rate.

2. The size selection performance is affected by minor changes in some critical dimensions. Damage or wear sufficient to change the performance significantly may not be detectable by a cursory examination.

A number of cyclones have been proposed to act as size selectors, and it would appear that most cyclones, if operated at a suitable airflow rate, would reasonably approximate the ACGIH size selection recommendations. However, as the size selection characteristics depend on the dimensions of the outlet as well as the cyclone, only instruments fitted with filters and tested complete should be used.

The greatest current interest is in small, personal gravimetric samplers. Of these there are two developments.

The personal gravimetric sampler, developed by British Cast Iron Research Association (18) and manufactured by Casella (M1), is a full shift, self-contained instrument. It has been calibrated both using spherical-monodisperse dusts and by comparison with a horizontal elutriator, and is stated to meet the MRC recommendation for respirable-dust sampling when operated at 1.9 ℓ/min.

A modification (19) to this sampler, by the U.K. Safety in Mines Research Establishment, is expected to be produced by Casella (M1) in the near future. In this, the cyclone is mounted on the cap lamp and the pump is mounted on the cap lamp battery, to simplify the application of personal sampling to underground miners.

The development of personal samplers in the United States has been based on the use of the Dorr Oliver 10-mm nylon hydroclone (M2). This has been used with different filter holders and calibrated by a number of workers (6, 8, 9, 10, 11). The recommended flow-rate, to meet the ACGIH specification, has ranged from 1.4 to 2.8 ℓ/min. Part of the differences between these may have been due to poor calibration techniques and part to differences between the assemblies. The latest compromise recommendation by the AIHA (7) is 1.7 ℓ/min for this particular cyclone, but this does not specify the filter.

A larger cyclone, the 1/2-inch HASL (6, M2), has been tested and the flow rate recommended (7) is 9 ℓ/min. This cyclone has also been made up as an externally powered, personal sampler for industrial use (20). These authors showed that when operated at 13 ℓ/min, this sampler collected 50% of the 5-μm unit-density spheres and the estimated respirable-dust concentrations were in good agreement with those estimated by the Hexhlett. Note this volume is much higher than would be expected from the AIHA recommendation (7) of 9 ℓ/min.

A still larger cyclone, the 1-inch HASL, has also been suggested (6, M2). There seems to be some error in the original calibration, 8.5 ft^3/min, by these authors and the correct flow-rate is likely to be near 5 ft^3/min (140 ℓ/min).

3. Miscellaneous Size Selective Samplers

A number of other size selective samplers have been proposed and some prototypes built (21, 22). These, while offering some advantages, all require calibration and none of them have advanced towards production. All of these depend on inertial and/or centrifugal forces to separate the dust. One, the conicycle (21), uses centrifugal force to deposit the respirable dust on the inside of a thin aluminum shell. This does not collect most of the dust below 1 μm in size, but the conicycle may be of interest in examining dusts where there are large quantities of fine particles, of different composition, present.

CONCLUSIONS

Two-stage, size selective sampling is an attempt to simulate dust deposition in the bronchial passages (mucous-swept) and in the alveolar regions of the lungs. The size selection recommendations simulate an 'average' healthy lung at the normal breathing rate and a size selective sampler estimates the dust hazard for such an individual.

Size selective samplers using horizontal elutriators can be designed, built and used with a minimum of calibration, whereas those using cyclones may need frequent careful calibration. It should be possible to maintain a personal sampling program by simple calibration comparisons between each cyclone sampler and either a master cyclone or a horizontal elutriator at regular intervals, preferably in a laboratory dust chamber*.

The Long-Period Dust Sampler is a very useful instrument for obtaining a sample of respirable dust for visual examination.

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* This laboratory chamber could be simple, consisting of a box with a circulating (mixing) fan and a number of mounts for the samplers. The dust supply could be standardized and supplied in small sealed cans for feeding with a simple compressed-air ejector as is done for the McIntyre prophylactic-aluminum powder.

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M1 Casella, C.F., and Co. Ltd., Regent House, Brittannia Walk, London W1, U.K.; Canadian Agent, Carleton Instruments Ltd., 2414 Holly Lane, Ottawa 10, Ontario.

M2 Union Industrial Co., 150 Cave St., Fall River, Massachusetts 02720, U.S.A.; Canadian Agent, Levitt-Safety Ltd., 33 Laird Dr., Toronto, Ontario.

TABLE 1

Recommended Size Selections for
Respirable-Dust Sampling

Aerodynamic Size	Fraction Passing Size Selector		
μm	MRC (2, 3)	USAEC (6)	ACGIH (7)
> 10		0	0
> 7.1	0		
5	50	25	25
3.5	75	50	50
2.5	87.5	75	75
2		100	90
< 2		100	

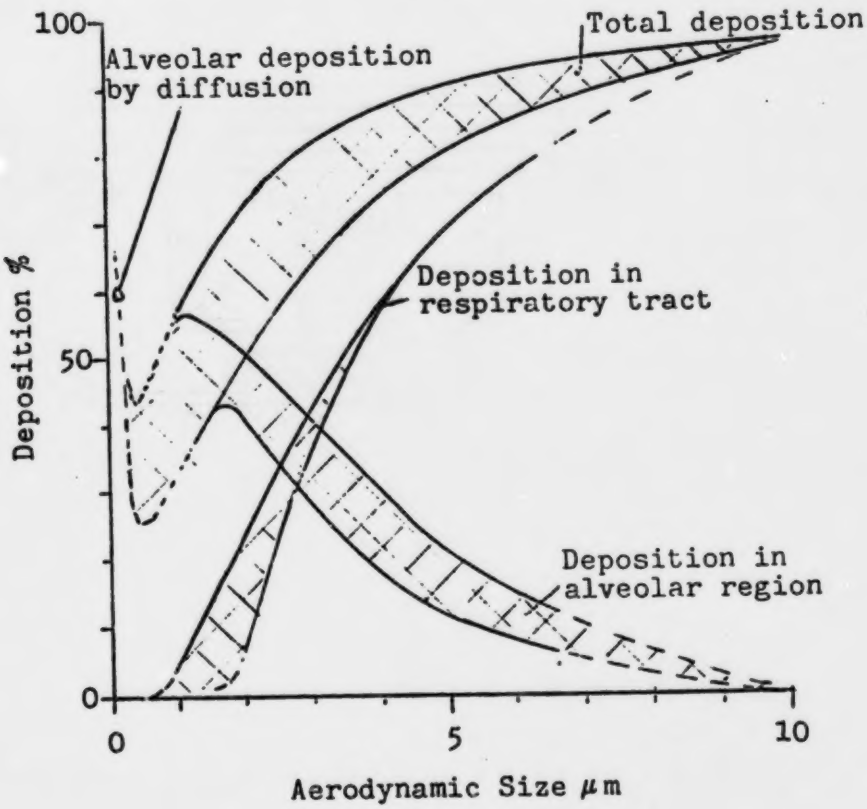

FIGURE 1: Dust deposition in the lungs, showing range of variation with the breathing rate

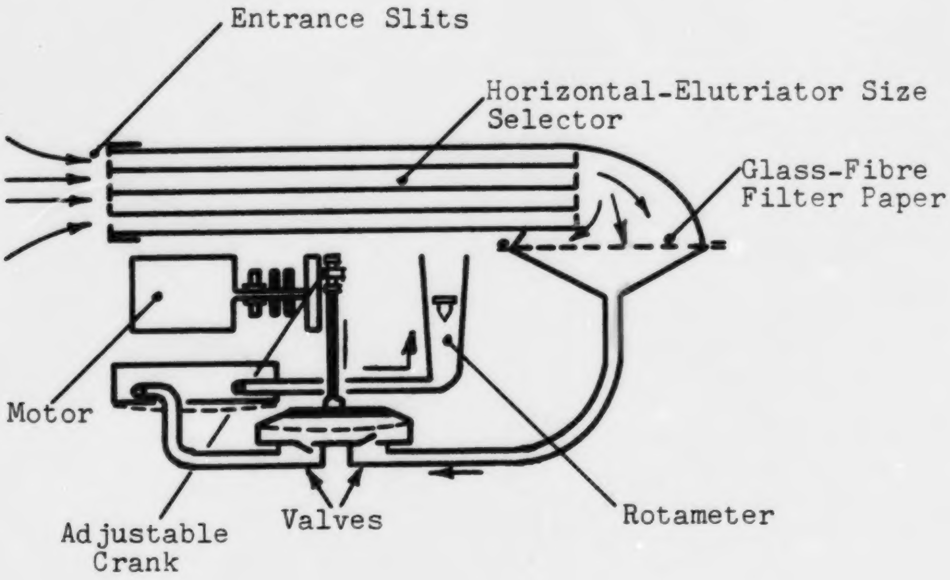
Entrance Slits
Horizontal-Elutriator Size Selector
Glass-Fibre Filter Paper
Motor
Rotameter
Valves
Adjustable Crank

FIGURE 2: SCHEMATIC DIAGRAM OF THE NCB MRE GRAVIMETRIC SAMPLER

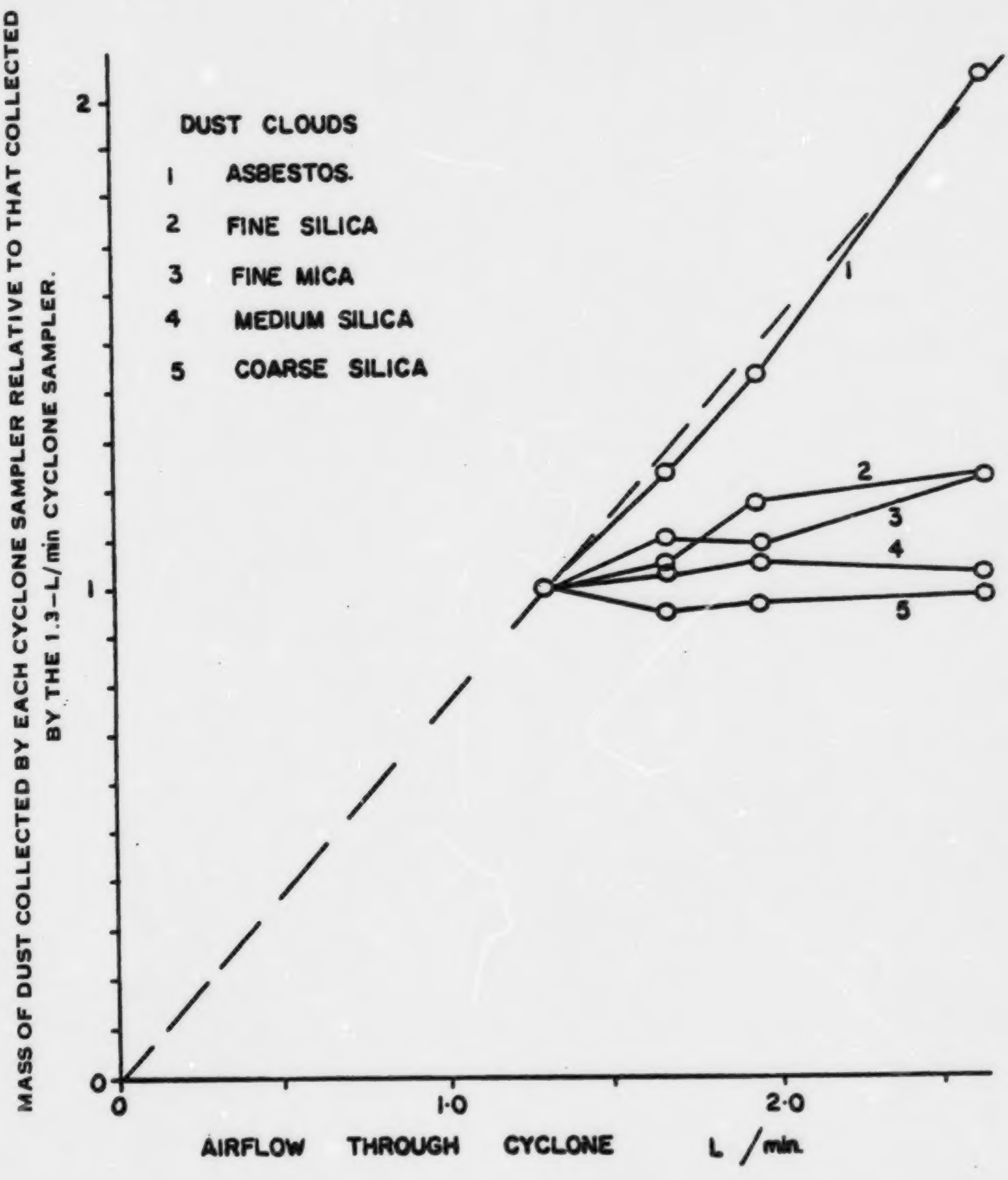

FIGURE 3: EFFECT OF AIRFLOW ON THE MASS OF 'RESPIRABLE' DUST COLLECTED BY CYCLONES

Section 5—Chapter 29

Routine Dust Measurements and Standards

by

T.S. Cochrane

The Canadian Mining and Metallurgical Bulletin
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MÉTHODES COURANTES DE MESURE DE LA POUSSIÈRE ET NORMES PROPOSÉES

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RÉSUMÉ

Le grand public étant de plus en plus renseigné sur les maladies professionnelles telle que la pneumoconiose, les corps législatifs et la main-d'oeuvre qualifiée s'en trouvent influencés. C'est pourquoi l'industrie minière canadienne doit accorder une importance primordiale à l'élimination des poussières. Il est, de ce fait, nécessaire d'effectuer des mesures et d'établir des normes permettant de maîtriser toute situation où la poussière représente un danger et de prévenir tout risque élevé à cet égard.

L'auteur traite de quelques méthodes de mesure utilisées, des normes proposées et de la terminologie utilisée dans cette technologie en plein essor. Il vise principalement à présenter les progrès de base accomplis par ceux qui ont utilisé les connaissances actuelles avec un certain succès.

☐ **ENVIRONMENTAL CONTROL — UNDERGROUND**

Routine Dust Measurements and Standards

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ABSTRACT

A growing public awareness of work-related diseases such as pneumoconiosis and the impact of this awareness on legislative bodies and on the skilled labour market are reasons why the Canadian mining industry must consider dust control of top-drawer importance. Measurements and standards related to the hazard are necessary to control a dust situation and to avoid excessive risk.

The author discusses some of the methods of measurement, standards proposed and terminology used in this developing technology. The purpose primarily in to give a better understanding of the basic advances achieved by those who have applied current knowledge with a measure of success.

INTRODUCTION

PNEUMOCONIOSIS is a disease caused by the accumulation of dusts, particularly insoluble dusts, in man's lungs. Because mining requires men to work in dust environments, the industry in most industrialized countries has taken steps to control both the dust production and the worker's exposure. Many methods of measurement have been developed to identify the hazard, to estimate the degree of this hazard and to assess the efficiency of control systems.

The purpose of this paper is to review in general terms the current multitude of choices of measurement methods and to discuss some of the factors which have given rise to them.

The Canadian mining industry has many reasons to consider the measurement of airborne dust and the defining of acceptable standards of prime importance. One reason is social pressure. During the on-going ecological revolution, the onus is on the industry to prove that environmental factors which may cause work diseases are under control. Failure to do so may invite arbitrary designation of measuring methods and acceptable limits instead of authoritative agreements based on the consensus of all interested parties.

Another reason is labour pressure. The worker is aware of the relationship between his health and his work environment. In the past, miners were able to exercise some control over their work environment. Today mechanization, which concentrates men, machines and power, results in high dust production and little individual control. The skilled miner required in the mines today is asking for some assurance that he faces no greater health risks than those in other industries. In a 'tight' labour market, this is a most important consideration if recruitment is to meet demand.

Still another reason, perhaps most important, is the realization that Canadian problems such as the dust problem can only be resolved in Canadian mines. Measuring techniques have been developed and tested in the laboratory, now these techniques must be validated in the field. Industry must accept the responsibility of generating this data if mine environments are to be conserved at an acceptable level and if the health of the worker is to be safeguarded. Lack of data does not necessarily reflect a non-existent problem.

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KEYWORDS: Environmental control, Underground mining, Coal mining, Dust control, Dust standards, Pneumoconiosis, Sampling, Exposure index, Toxicity.

BASIC CONSIDERATIONS

1. Dust particles range in size from 0 to 400 microns. Particles greater than 10 microns are considered large and can be seen with the naked eye. Those particles from 1 to 10 microns and less than 1 micron are invisible to the naked eye and are considered fine and ultrafine respectively.

2. The deposition of dust in the respiratory tract is dependent on the airway dimensions and respiratory characteristics of the individual as well as the aerodynamic properties (settling velocities) of the dust particles. All particles less than 5 microns in diameter escape the filter system of the upper respiratory tract and lodge well into the lungs. Smaller sizes — less than 3 microns — enter the alveoli.

3. All dust is foreign to the respiratory system and under normal circumstances is removed to a considerable extent by natural body protective mechanisms. The amount of dust retained by the lungs is the difference between dust deposition and dust clearance.

4. Disease such as pneumoconiosis results from a breakdown of the protective system due to excessive dust accumulation in the lungs, or to chemical or toxic action of the dust lodged in the lung tissue.

5. All dusts activate the elimination systems of the body, but not all dusts are pathogenic. The toxicity of a pathogenic dust is proportional to its surface area. Insoluble mineral dusts give rise to the most severe and permanent damage to the lungs; and silica, the worst of the mineral dusts, causes permanent fibrogenic lung damage.

6. Pneumoconiosis cannot be cured, just prevented. However, simple pneumoconiosis caused by the action of dust alone leads to little disablement. Progressive massive fibroses are complications of well-established cases of simple pneumoconiosis. Chest X-rays of the lungs show opacities caused by dust, but before the symptoms and signs are clearly evident the disease is well established and some degree of disablement occurs.

7. Individual susceptibility is too complex to define an average-man model, but evidence points to disease-resistant and disease-prone individuals at the extremes.

DUST MEASUREMENT

No 'universal' measuring method exists and furthermore, on the basis of present biological knowledge, it is very unlikely that a best method will evolve. It is more important for all concerned to reach a consensus of opinion on the effective use of current methods of measurement with a full understanding of their applicability and the accuracy and precision of the data generated.

Dust measurement consists of two distinct activities — sampling of the suspended cloud and assessment of the sample in accordance with a risk concept. Ideally, the sample should be representative of the dust reaching the critical organ of the worker, in this case the lungs, and the assessment should identify the degree of hazard involved.

The many methods of measurement developed for and used by the mining industry can be classified as either non-selective or selective and grouped into subcategories on the basis of sampling and assessment characteristics, as shown in Table 1.

Non-Selective Measurement

Non-Selective Sampling

Non-Selective Assessment

Single-stage samplers are used to collect a portion of the total dust — respirable and non-respirable. The upper size cut-off is dictated by the mechanical characteristics of the sampler — orifice shape, dimension and flow rate. The total sample collected is assessed by weighing, light scattering or light extinction techniques. Results are reported as gross mass concentrations or projected surface areas (photo-electric ratios).

Justification for this method of measurement is based on the following assumptions:

all inhaled dusts are toxic (<10 microns);
dust, when absorbed by the body system, contributes to harmful effects;
the particle size distribution of mineral dusts is relatively constant and a fixed ratio between total and respirable dust can be assumed.

Because of the simplicity, reproducibility and low cost of the method, it is particularly adaptable to control sampling. At the same time, because of the sensitivity of the method to particle size distribution, care must be taken to limit its use to monitoring a simple dust generating operation in uniform conditions. In other words, the selectivity not built into the method must be exercised by the dust control officer.

Selective Measurement

Non-Selective Sampling

Selective Assessment

The samplers collect a portion of the total dust, respiratory and non-respiratory. The respirable fraction is graded by linear dimension using reference samples of known dimensions as guidelines. Concentrations are expressed on the basis of number particles in a given size range, normally 1-5 microns for coal and 0.5-5 microns for mineral dusts.

The basic assumptions underlying this measurement method are:

only dust that enters the lungs, the respirable dust, contributes to the pneumoconiosis hazard;
dust under 5 microns in size escapes the filter system of the upper respiratory tract and is capable of passing the airway dimensions to the lungs;
mineral dusts in general can be considered regularly shaped particles and can be specified by one linear dimension.

TABLE 1 — Routine Dust Measurements

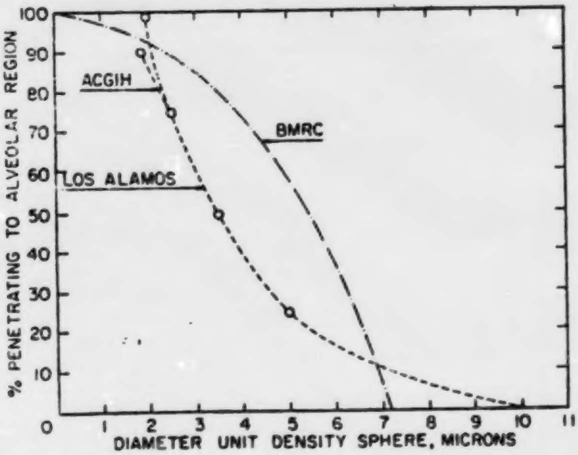
NON-SELECTIVE MEASUREMENT Total	SELECTIVE MEASUREMENT Respirable		
Non-Selective Sampling Non-Selective Assessment	Non-Selective Sampling Selective Assessment (linear)	Selective Sampling Non-Selective Assessment (aerodynamic)	Selective Sampling Selective Assessment (aerodynamic)
open filters, high-volume filters: paper, membrane, vinyl, soluble glass fibre, etc. gravimetric, mass, mg/^{3}	impinger, konimeter, thermal precipitator, microscopic, number, ppcc, mppcf	cyclone-filter, elutriator-filter, gravimetric, mass, mg/m^3	selective samplers. X-ray diffraction, infra-red spectroscopy, per cent, mg/m^3
thermal precipitator photoelectric, projected area ratio, per, pam	tyndalloscope, sedimentation, light scatter, mass, mg/m^3	elutriator-thermal precipitator, microscopic, number, ppcc, mppcf.	
electrostatic precipitator gravimetric, mass, mg/m^3	impinger, konimeter, thermal precipitator, automatic, electric, number, ppcc, mppcf	impinger, thermal precipitator, diffraction size-frequency analyzer, respirable surface area, RSA (square microns per cubic centimetres)	techniques not fully developed
dust control	dust control	exposure control	dosage control

The method of measurement is simple in application, but is deficient in many desirable factors. The short-term instruments have a low sampling rate and, consequently, several samples are required to define a dust source; this adds to the unit cost. Imprecision is inherent in both the sampling and the assessing techniques. Sampling errors are introduced by the break-up of aggregates, the overlapping of particles and the short-term grab characteristics of some of the instruments. Errors in assessment are related to the training and experience of the counters and the irregularity of particle shapes. The total error is a minimum of 20 per cent under the best of circumstances.

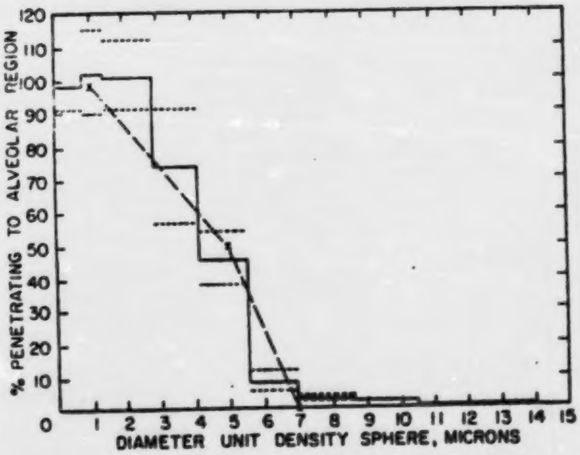
Selective Sampling

Non-Selective Assessment

In recent years, there has been an increasing movement toward selective sampling of respirable dust. Proponents of this movement claim that the measurement method used must generate data on the dust which reaches the lungs of the worker. To do this, the sampler must emulate the size-selective characteristics of the human respiratory tract and fractionate the dust on the basis of its aerodynamic properties. Particle shape and density differences are automatically taken into consideration.



(A) BMRC, LOS ALAMOS, AND ACGIH SAMPLERS



(B) IMPINGER THERMAL PRECIPITATOR

FIGURE 1.

Experimental lung deposition data and regional deposition and clearance dynamics (calculations) have been used to generate sample acceptance curves. Samplers have been developed to match these requirements. Figure 1 illustrates some of the efficiency vs size characteristics of these samplers.

Most respirable dust samplers are two-stage units which incorporate a horizontal elutriator or cyclone as first-stage collector and filters in the second stage. Some conventional short-term samplers such as the thermal precipitator have been fitted with pre-separators in place of standard cut-off systems. Assessment of collected samples is principally by weighting and by diffraction.

The method of measurement combines the sampling and assessment techniques considered superior for insoluble mineral dusts which affect the lungs. Designed principally for sampling the pneumoconiosis producing dusts in the general body of the mine air (positional samplers) and in the breathing zone of workers (personal samplers), the use has been extended to give a dust control capability.

Limitations of the method are related to: the data base for the lung retention curves, which are subject to questioning and modification, the sensitivity of the first stage (the collector) to flow rate and to entrainment, requiring careful instrument maintenance and calibration, and selected use.

Selective Assessment

This is only a developing method of measurement and has yet not reached the routine stage.

Selective samplers are used to collect the respirable dust particles. The toxic dust within the respirable portion is identified and quantified. To date only the identification of quartz using X-ray or infra-red techniques has reached the routine stage.

This type of measurement is advanced on the theory that factors other than concentration lead to the development of pneumoconiosis. Toxicity of the dust and the surface area of this dust are considered the more likely causes in many instances. The major limitation of the method rests with the fact that the relative toxicities of the various mineral dusts have not been established by epidemiological studies.

DUST STANDARDS

If it is agreed that measurements are essential to understand and define the quality of mine air from a dust viewpoint, then it follows that dust standards are necessary to give the measurements some relevance. In the formulation of dust standards, many factors pertaining to both the dust and the worker must be considered and weighed. Unfortunately, because of the scarcity of data, particularly biological data, many assumptions and approximations must be made and it follows that sophistication in setting standards is unwarranted. Nevertheless, target figures should be set and accepted with the full understanding that they are interim, based on the best of current research and experience, and subject to revision as more knowledge becomes available.

Three types of yardstick are used as guidelines by the mining industry: the dust index; the exposure index; and the dosage index.

Dust Index

The dust index standard is based wholly on the principle of continuous improvement in the control of dust at the source. Intermittent sampling is carried out to pinpoint dust operations and/or places of work during periods of maximum dust production. The results of a series of measurements are combined and reported as a dust index for the particular operation or working place. Indices for a mine may be compiled to calculate an over-all mine dust index. Indices for similar operations, mine geometries or mines in total are compared throughout the industry and levels of acceptability are established — satisfactory, borderline or unsatisfactory. These levels of acceptability are maximal acceptable concentrations or ceiling values below which all values should fluctuate.

Table 2 is an example of dust indices measured and calculated for a gold mine in South Africa.

Short-term non-selective samplers and non-selective assessment are particularly suited for this type of control because of the simplicity, flexibility and low cost. The appeal is for the on-the-spot or quick assessment.

Exposure Index

The exposure index standard is based on the principle that respirable dust is a substance to which repeated exposure (cumulative effect) is necessary to cause disease. The yardstick is the lifetime weighted average defined as the sum of different exposures experienced by a worker multiplied by the length of time he will be exposed to these various exposure rates over his entire work period. For mining, the time parameter is based on an 8-hour shift, a 40-hour week and a 30- to 35-year work span. The limits of acceptability are usually defined as threshold limit values, the time weighted concentrations throughout the 8-hour daily operations. In many instances, to give a greater degree of flexibility for many operations, the limit of acceptability is expressed as a mean average concentration or mean permissible concentration over an extended period — a week, a month, a quarter, etc.

Because these standards are averages, judgment must be exercised as to the degree of fluctuation about the limit for short periods such as one hour in 8 or one day in 30. This is why it is extremely difficult to have rigid statutory enforcement and why experience and common sense must be used. Some of the current accepted exposure limits are listed in Table 3.

TABLE 2 — Dust — Index Standard

Section of mine	Average dust level in this section	Number of workers in this section	Weighted dust level for section
1	240	110	26,400
2	360	272	97,920
3	220	148	32,650
4	490	221	108,200
5	370	137	50,690
6	150	94	14,100
7	410	255	104,550
	Total	1,237	434,510

$$\frac{434{,}510}{1{,}237} = 350$$

Calculation of Mine "Dust Index" (1)

Long-term selective samplers and non-selective assessment are the most commonly used for establishing exposure-index standards.

Dosage Index

The dosage index standard is based on the principle that a definite dosage relationship exists and that a worker can only be exposed to a toxic rated dust for a specified time if no harmful effects are to be expected. The dosage index standard is comparatively new and is not widely used because agreement cannot be reached on the toxicity factors allocated to the various dust minerals.

The control system used in West German coal mines (see Table 4) is perhaps the prime example of a dosage standard. A risk number index, based on concentration quartz content, is used to classify the work atmosphere and a health index is used to classify the worker. The two indices are combined to determine the disposition of the worker in the mine and the maximum number of shifts allowable under certain combinations.

The recent trend toward quartz equivalent indices instead of dust indices and quartz-mppcf-years in-

TABLE 3 — Exposure — Index Standards

A. Proposed A.C.G.I.H. Threshold Limit Values(2)

% Quartz	Respirable Mass T.L.V.	Total Mass T.L.V.
100	0.10 mgm/cu m	0.29 mgm/cu m
80	0.12 mgm/cu m	0.37 mgm/cu m
50	0.19 mgm/cu m	0.58 mgm/cu m
20	0.46 mgm/cu m	1.40 mgm/cu m
0	5.00 mgm/cu m	15.00 mgm/cu m

Formulae: Respirable Dust $\frac{10}{\%\ \text{Respirable}\ SiO_2 + 2}$ mg/m^3

Total Dust $\frac{30}{\%\ SiO_2 + 2}$ mg/m^3

B. Approved Dust Conditions — British Coal Mines, 1970(3)

Working Place/ Operation	Minimum Sampling Frequency (Previous minimum frequency in brackets)	Approved if: –
Coal face production shifts: coal drivages	Once per month (Twice per year power-loaded faces; elsewhere once per year)	Mean of last three monthly concentrations does not exceed 8 mg/m^3
Stone drivages	Once per month (Once per year)	Mean of last three monthly concentrations does not exceed 3 mg/m^3
Loading and transfer points in return airway	Once per quarter (Once per year)	Mean of all results taken during the month does not exceed 8 mg/m^3
Coal face cutting shifts	Once per half-year (Once per year)	do
Coal face preparation shifts	Once per year (Once per year)	do

stead of lifetime averages are indications of the direction that standard setting will take place in the future, particularly in mines other than coal mines. Accordingly, selective sampling and the selective assessment type of measurement will grow in importance.

APPLICATION IN INDUSTRY

The task of choosing one method of measurement and standard setting for the many different types of mines, strata conditions and dust producing operations in a mine is most difficult and complex, if not impossible. However, the task of choosing for one particular mine or one particular type of operation becomes less complicated. It may be stated that any of the methods of measurement can be used effectively to monitor improvement in dust conditions if the necessary skill and experienced persons are available and the costs in terms of time and money are unlimited. On the other hand, from experience and association with the problem, the writer feels that very few measurements are suited for routine application.

On the basis of present knowledge, it can be said that the pneumoconiosis risk at mines is related to the dust load and the dust toxicity. Also, in the opinion of the writer, the risk is most severe at the extreme ends of the spectrum where the dust loads are high and the toxicity relatively low or where the toxicity is high and the dust loads are relatively low.

TABLE 4 — Dosage Standards, West Germany (4) Silicosis Research Institute

Dust Mineral Factors

Group	Mineral Factor	Minerals
A	1.2	Cristobalite (in calcined diatomaceous earth)
B	1.0	Quartz, cristobalite, tridymite
C	0.7	Talc, steatite, asbestos
D	Quartz >25% = 0.7 " 6-25% = 0.5 " 1- 5% = 0.3 " 0% = 0.2	Mica Group: mica-like minerals, feldspar, hornblende, augite, chlorite, serpentine, sillimanite, mullite, fluorspar, virtreous amphorous sinter products, amorphous SiO_2
E	0.2	Clay Group: clay minerals, hydrated amorphous SiO_2
F	0.1	Ore and Carbonate Group: carbonates, sulphates, sulphides (excepting their Ca-compounds) dolomite, magnesite, barite, siderite, Pb, Zn, Cu, Mn ores, pyrites
G	0.01	Coal Group: coal, coke, soot, graphite
H	0.01	Iron oxide Group: Fe-oxide, hydroxides, limonites, hematite etc.
I	0	Alkali Group: calcite, gypsum, rocksalt, potash salts

$$\text{Dust Value} = \frac{\text{tyndalloscope dust cone} \times \text{dust mineral values}}{10}$$

$$\text{Dust Mineral Value} = \text{\% of mineral by weight} \times \text{mineral factor}$$

COAL MINING ASSOCIATION

$$\text{Dust Sum Value} = \text{tyndalloscope dust cone} \times \text{dust mineral value} \times \text{number of shifts}$$

Proposed Tolerance Levels:

Dust Sum Values

10,000 per year 40,000 per 5 years	Mines with normal X-rays
8,000 per year	Miners in restricted category

Dust Load

Where the significant parameter is the dust load and where the hazard is the cumulative effect of these high dust loads on the workers, a selective sampling — non-selective assessment method based on the gravimetric sampling of respirable dust at strategic points throughout the mine should be adopted and an exposure index standard set. The samplers should be positional samplers and the relationship between the samplers' exposure and the workmen's exposure established and checked periodically by a specially trained team using both personal and positional samplers. Remember, it is the worker not the instrument or the position that is subject to dust diseases.

Dust Toxicity

Where the toxicity of the dust is the significant parameter, the selective sampling - selective assessment techniques would be recommended. However, these techniques have not been developed to the routine stage. Because of the cyclic nature of the mining operations involved, the mobility of the personnel and the irregularity of ventilation in open areas, the average exposure standards are not realistic. Correlation is too difficult.

Under these circumstances, the strategy should be to pinpoint dust sources and set dust-index standards, or ceiling values, for these operations. This can best be done by monitoring peak dust-production periods, and the method of measurement recommended is the non-selective modified short-term sampling and automated non-selective assessment method. Most of the other measurement systems can be used; however, the one-shot snap samplers and the microscopic assessment of dust spots are rejected on the basis of high inherent errors in the techniques.

CONCLUDING REMARKS

The eradication or reduction of pneumoconiosis to an acceptable level rests with continuing investigation by medical and technical investigators into the cause-effect relationship. One of the most important contributions to the cause is the introduction of data-generating dust programs in each and every Canadian mine based on developed measurement and standard-setting techniques applied with understanding and responsibility.

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Section 5—Chapter 30

Personal Dust Sampling in Mines: Statistical Analysis

by

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ÉCHANTILLONNAGE DE LA POUSSIÈRE À LAQUELLE EST EXPOSÉ LE PERSONNEL MINIER : ANALYSE STATISTIQUE

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__Résumé__. L'exposition à la poussière de tous les mineurs souterrains varie beaucoup d'un jour à l'autre, même s'ils effectuent la même tâche dans le même chantier. Cette variabilité suit une distribution log-normale avec un écart-type géométrique d'environ 1,6 dans les trois évaluations de la poussière (poussière inhalable totale, poussière combustible inhalable et poussière de quartz inhalable) effectuées dans les deux mines à l'étude. La variabilité était homogène pour tous les mineurs et pour la plupart des tâches. Les différences observées chez des mineurs exécutant les mêmes tâches ne se sont pas avérées significatives de sorte qu'il est proposé de déterminer dans le cadre du programme d'échantillonnage de la poussière la moyenne d'exposition de chaque tâche et de l'utiliser comme taux représentatif d'exposition de chaque mineur.

PERSONAL DUST SAMPLING IN MINES: STATISTICAL ANALYSIS

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Abstract. It is shown that the dust exposure of all underground workers varies greatly from day to day even though each man did the same job in the same working place each day. The variability follows a logarithmic normal distribution with a geometric standard deviation of about 1.6 for the three dust assessments; total respirable dust, respirable combustible dust and respirable quartz dust in both mines studied. The variability was homogeneous for all men and most jobs. The differences between men doing the same job was found not to be significant and it is suggested that the dust sampling program should determine the average for each job and use this as the best estimate of the exposure for each man.

INTRODUCTION

This study forms part of the dust and radon project in the minerals program of the Department of Energy, Mines and Resources Canada and is a continuation of our work presented at the First International Ventilation Congress (1).

Dust sampling in mines is carried out to assess workers exposure, efficiency of dust controls and need for more dust controls. The main potential dust hazard, in many mines, is the quantity of airborne free silica present. The major problem in assessing its hazard is the variation in the crystalline form, variety and impurities (2) which affect both the biological (3) and analytical response (4). The admixture with other minerals may also inhibit the biological reaction to quartz. Thus it is necessary to standardize analytical techniques and calibration methods, and to recognize that there may be substantial differences in the equivalent biological response to silica dust concentration in different mines. Low response to quartz has been demonstrated in coal mines and brick works (5, 6). This variability can only be estimated by epidemiological studies after an accurate reproducible index of free silica exposure is obtained.

The development of instrumentation, has been covered in previous papers (1, 7), which have described the rationale and development of the Elliot Lake Laboratory's CAMPEDS dust system which incorporates quartz assessment by X-ray diffraction on each sample, gravimetric assessment before and after ashing and a personal full shift size selective sampler combined with the miner's cap lamp battery.

One major difficulty is the very great variability of dust exposure for each man from day to day and is the subject of this report together with its effect on design and interpretation of sampling programs.

SAMPLE COLLECTION

Dust samplers used were the CAMPEDS units. The issue and daily set up of these was the responsibility of mine ventilation department staff at two mines following Elliot Lake Laboratory methods (8).

The preparation and analysis of filters were carried out in the Elliot Lake Laboratory (7), and statistical analysis of the data was carried out at the Mineral Sciences Laboratory in Ottawa.

The design chosen for sample collection was to concentrate on one beat[+] at a time taking samples on about 6 men each day for a week. In the second mine the coverage became wider in the later samples. Results returned from the mine included: date, man code; beat or working place designation; sampler; air flow rate before and after sampling; filter number; cassette number; instrument number; running time indicated on sampler and that by external clock.

Analysis in the laboratory produced: total respirable dust from weighing filter before and after sampling; respirable combustible dust as weight loss on ashing, and respirable quartz dust by one X-ray diffraction assessment on each of the two lines with Miller indices of 1,0,1, and 1,1,2. The average of the two lines is used.

While the samples have been taken from portal to portal of the mine some errors have crept in due to running the samplers on surface and failure to run them underground. To minimize error in estimating exposure it is considered that nominal concentrations based on a working day of eight hours are more suitable than the concentrations based on the recorded times because they can be related to the nominal working day assumed in defining threshold limit values (9). Some samplers had been accidentally switched off underground for various periods and the results of these were corrected by assuming a constant concentration over the underground shift and multiplying them by the nominal running time. This correction has been applied to all full shift samples with indicated running times between 200 and 400 minutes. Samples with running times greater than 400 minutes were assumed to have run the full shift.

It should be noted that combustible dust determinations were only carried out on visibly blackened filters and are only representative of samples with substantial exposure to diesel exhaust particulates.

The sampling was carried out in two mines, both working ore in a host rock consisting mainly of quartz pebbles in a quartzite matrix. The quartz content of the rock was about 65% and the quartz content of the airborne mineral dust in the respirable size range was about 50%. Mine A was a trackless mine using large diesel-powered equipment. Mine B used jackleg drills and slushers to remove the broken ore into a track haulage system plus a trackless area similar to Mine A.

STATISTICAL ANALYSIS

Most men worked on the same job in the same area on each of their sampling days, and most working places are only represented by one man; thus there is a direct interaction between men and working places.

The analysis was carried out on logarithms to the

[+] A beat is an area under one first line supervisor.

base 10 (log) of the dust concentrations as has been usual for many air sampling studies (10). This leads to the geometric mean (GM) and geometric standard deviation (GSD) as the usual statistical descriptors. Because exposure is the sum of each days dust, arithmetic means (AM) are also given in some Tables.

An example of the full results for one statistically average job (underground mechanics) is given in Table 1.

The analysis was carried out within and between classes in various groups of jobs. Classes used were men, jobs and areas, and groups were all drilling, mucking, other mining and underground non-mining. First line supervisors were included in "other mining jobs". "Non-mining jobs" included mechanics, electricians, pumpmen, and surveyors. Statistical analysis results for total respirable dust (TRD) and respirable quartz dust (RQD) are given in Table 2. It can be seen that the variation within each class is high for both total respirable and quartz dusts with geometric standard deviations ranging from 1.3 to 2.05. The variance between classes is somewhat lower ranging from non-significant to geometric standard deviation of 1.6.

Cochrane's and Bartlett's methods were applied and indicated that the variability of the samples in each class were inhomogenious to a significance level of 90 to 97%. However, these tests do respond to departures from normal distribution which result from the low numbers in each class and it is assumed that the variance is homogeneous in each class of man, most jobs and mining areas. The non-mining areas have an odd distribution of jobs and may not be homogenous.

Because each man worked on one job in one area during this study, it can be expected, as found, that the variance for one man is less than that for one job which necessarily includes the variance between men and between areas. Similarly that for areas can be expected to be greater. It can be seen that in the main mining jobs, drilling and mucking, the difference between men, jobs and areas is small or insignificant. The ancillary mining and non-mining jobs showed greater variability.

Effect of Job

The mean values for each job in the two mines are

Table 1. Example of Full Results for One Job

DATE	MAN'S NO.	AREA NO.	JOB NO.	DIAL TOT.	TIME TOT.	FLOW BEF.	FLOW AFT.	TOTAL RESP. MG/M**3	RESP. COMB. MG/M**3	RESP. QUARTZ UG/M**3
78016	2049	1	204	412	421	2.1	2.1	1.01		255.
78017	2049	1	204	482	479	2.1	2.1	.84		143.
78017	2050	1	204	502	495	2.1	2.1	.41		48.
78017	2050	1	204	342		2.1	2.1	.32		42.
78017	2049	1	204	523	485	2.1	2.1	.72	.49	49.
78026	2049	1	204	493	495	2.1	2.1	.48		200.
78030	2050	1	204	522	531	2.1	2.1	.38		75.
78056	2079	1	204	532	530	2.1	2.1	.32		45.
78057	2078	1	204	492	495	2.1	2.1	.26		76.
78067	2081	1	204	367	496	2.1	2.1	.15		38.
78067	2080	1	204	505	502	2.1	2.1	.35		125.
78068	2078	1	204	441	495	2.1		.09		
78067	2079	1	204	483	496	2.1	2.0	.34	.32	41.
78068	2081	1	204	461	488	2.1		.15		31.
78068	2080	1	204	343		2.1		.48		
78068	2079	1	204	535	534	2.1	1.9	.38		43.
78065	2079	200	204	480	496	2.1		.45		98.
78163	3066	286	204	525	525	2.1	2.1	.09		47.
78164	3066	286	204	327	495	2.1	2.1	.25		25.
78100	2075	400	204	410	532	2.1	2.0	.38		89.
78101	2075	400	204	526	532	2.1		.38		48.
78102	2075	400	204	343	494	2.1		.73	.50	63.
78103	2075	400	204	391		2.1		.64	.38	47.
78065	2081	600	204	490	493	2.1	2.1	.26		41.
78066	2081	600	204	477	492	2.1		.16		31.
78100	2074	700	204	531		2.1	1.6	.66		173.
78101	2074	700	204	383	535	2.1	1.6	.49		95.
78102	2074	700	204	526	535	2.1	2.1	.38		49.
78103	2074	700	204	532	539	2.1		.82		205.
78065	2078	800	204	514		2.1	1.0	.49		51.
78066	2078	800	204	486	492	2.1		.17		38.
78154	3061	804	204	497	520	2.1	2.1	.18		44.
78158	3057	844	204	503	515	2.1	2.1	.24		110.
78152	3045	885	204	497	543	2.1	2.1	.37		72.
78065	2080	900	204	441	496	2.1	2.1	.67		309.
78066	2080	900	204	164		2.1		.07		21.
77349	2019	902	204	430		2.1	2.1	.64		90.
	4002	1000	204	484	496	2.1	2.1	.35		203.
	4965	1100	204	400		2.1	1.9	.18		22.
78061	2062	6040	204	474	465	2.1	2.0	1.81	1.28	201.
78058	2062	6245	204	510	508	2.1		.19		31.
78060	2062	7215	204	263	420	2.1	2.0	.51	.46	49.

Table 2. Analysis of Variance Within and Between Classes

Group Class	Total Respirable Dust Number Classes	Number Samples	Geom. Std. Dev. Within	Between	Mean mg/m^3 Geom.	Arith.	Respirable Quartz Dust Number Classes	Number Samples	Geom. Std. Dev. Within	Between	Mean µg/m^3 Geom.	Arith.
MINE A												
All jobs												
men	37	154	1.3	1.7	.54		37	152	1.7	2.2	32	
jobs	9	161	1.6	1.6	.55	.68	9	159	2.0	2.0	32	70
beats	8	161	1.6	1.5	.55		8	159	2.0	2.0	32	
Drilling												
men-beats*	6	27	1.4	1.4	.52	.57	6	27	1.6	1.6	23	27
Mucking												
men-beats*	6	20	1.4		.76	.80	6	20	1.8	1.7	53	65
Other mining												
men	25	107	1.7	1.8	.50		24	107	1.7	2.5	30	
jobs	6	109	1.6	1.7	.52	.67	6	107	2.1	2.2	31	82
beats	8	109	1.6		.52		8	107	2.1	2.2	31	
MINE B												
All jobs												
men	244	712	1.7	1.6	.45		301	746	1.8	1.6	81	
jobs	77	869	2.1	1.3	.44		77	869	2.0	1.3	81	108
areas	24	869	2.1	1.3	.44	.58	24	869	2.1	NS	81	
Drilling												
men	65	159	2.0	NS	.44		72	173	2.2	NS	77	
jobs	7	219	2.1	1.2	.41		7	223	2.3	NS	76	111
areas	16	217	2.2	NS	.41	.54	16	221	2.3	NS	77	
Mucking												
men	85	201	1.6	1.3	.42		85	201	1.8	1.5	86	
jobs	7	276	2.2	NS	.40		7	276	2.2	NS	82	114
areas	16	276	2.1	1.3	.40	.56	16	276	2.1	1.2	82	
Other mining												
men	74	164	2.0	1.4	.46		73	164	2.0	1.4	81	
jobs	13	239	2.1	1.3	.44		13	239	2.1	1.3	80	106
areas	18	288	2.1	NS	.44	.59	18	238	2.1	NS	81	
Non-mining												
men	26	87	1.7	1.6	.44		27	84	1.7	1.5	58	
jobs	7	105	2.0	NS	.42		7	102	1.9	1.3	59	75
areas	13	104	1.8	1.4	.42	.53	13	101	1.9	NG	59	

* During this study mostly only 1 man in each beat was sampled.

given in Table 3.

In Mine A, in this study the conveyor belt operators are exposed to the highest quartz dust levels, the scooptram operators and rockbreakers to medium levels and the other jobs to low levels.

In Mine B the effect of job on TRD and RQD exposure is small and the differences are insignificant with the exception of the 25% lower quartz exposure for the non-mining group. The difference in quartz exposures between drilling and mucking is much less than the difference in quartz dust produced by these two operations which is normally in a ratio of 1 to 10 in a shifts' work (1).

Effect of Area

The mean values for each area considered in the mine are given in Table 3. Whilst there are substantial differences in some areas, these tend to reflect the large differences in activity between the areas. For instance, in Mine A beats 107 and 112 are markedly low while 117 is markedly high. These three beats differ in job breakdown from the rest as shown in Table 4. It is also clear that the sampling distribution did not match the job distribution. The second mine had a better match between sample and job distribution. The differences between the active mining areas were not significant, and the areas without active mining; 1,2,5000 and 6000 tended to have lower quartz concentrations.

DISCUSSION

It is clear that the very great variation in the dust exposure of each man from day to day is a major problem in setting up and interpreting a dust sampling program.

The precision with which a mean dust concentration is estimated from a number of samples is shown in Fig. 1. Even after 50 samples the mean can only be estimated to a precision of ± 15%.

Various other representations of the variability have been prepared and some examples for quartz dust concentrations are given in Figs. 2 to 5. It can be seen that the distribution with respect to the mean for each job (Fig. 4) is only slightly narrower than that for all samples (Fig. 2). Whilst the distribution for each man appears substantially narrower (Fig. 5), this is partly an artifact of the small numbers, 3 to 5, of samples for each man and the resultant bias of the mean towards the extreme values.

It is surprising that the variability is almost the

Table 3. Mean for Each Job and Area

#	Job Title	Total Resp. Dust				Combustible Dust				Quartz Dust			
		N	GSD	Means mg/m^3 Geom.	Arith	N	GSD	Means+ mg/m^3 Geom.	Arith	N	GSD	Means μg/m^3 Geom.	Arith
	Mine A												
42	Driller Jumbo	20	1.6	.52	.57	11	1.4	.59	.62	20	1.7	28	32
43	Driller Long Hole	8	1.4	.59	.62	3	1.2	.59	.60	8	2.0	14	17
38	Scooptram Op.	24	1.4	.76	.80	20	1.6	.57	.62	24	2.0	53	65
31	Ore Truck Op.	14	1.3	.46	.47	8	1.2	.40	.41	14	1.6	26	29
39	An/Fo Loader	17	1.4	.50	.53	13	1.6	.45	.49	16	1.5	25	26
40	Rock bolter	22	1.6	.52	.57	11	1.3	.53	.54	22	1.9	30	36
47	Conveyor Belt Op.	13	2.1	1.47	1.92	12	1.6	.68	.76	13	4.1	184	450
59	Rock Breaker Op.	13	1.3	.73	.75	12	1.4	.52	.55	13	2.0	41	51
80	First Line Super.	30	1.5	.30	.34	5	1.8	.38	.43	29	2.1	16	24
	Mine B*												
304	Driller Jackleg	21	2.8	.32	.43	4	1.2	.34	.34	22	2.7	55	74
421	" "	42	1.7	.60	.68	3	2.7	.20	.28	42	1.9	79	96
501	" "	105	1.8	.37	.44	2	1.0	.27	.28	106	2.1	68	92
311	" Jumbo	33	2.7	.58	.79	9	1.8	.57	.65	33	1.8	79	92
302	Mucker Raildrift	14	1.8	.51	.61					14	1.6	78	85
503	Slusher Stope	216	2.0	.38	.47	8	1.5	.17	.18	216	2.0	101	130
313	Scooptram Op.	30	2.1	.87	1.07	12	1.4	1.04	1.10	30	2.1	103	131
303	Trammer Drift	92	2.1	.50	.75					94	2.2	99	146
315	Service Drift	18	1.7	.98	1.12	5	1.6	.73	.79	18	1.8	100	118
506	Service Stope	47	1.9	.41	.58	2	1.6	.22	.24	47	2.1	81	107
316	Rockbolter	15	3.1	.30	.50					15	2.2	33	44
505	"	21	1.9	.46	.52					21	1.6	120	136
210	First Line Super.	22	1.7	.33	.38					22	1.7	60	70
202	Deckmen	11	1.9	.56	.71	2	1.2	.25	.26	11	1.9	62	77
204	U/G Mechanics	40	2.4	.40	.59	11	1.8	.52	.62	36	2.6	64	111
205	U/G Electricians	36	2.8	.44	.63	15	1.6	.60	.67	36	1.7	44	51
	Mine A Beats												
101		28	1.6	.57	.63	17	1.5	.45	.48	28	1.9	38	47
102		29	1.7	.42	.48	13	1.5	.42	.45	28	1.9	28	36
103		26	1.4	.70	.74	23	1.4	.65	.67	26	2.0	36	45
104		24	1.5	.48	.53	15	1.5	.47	.51	24	1.7	28	33
105		16	1.5	.57	.61	9	1.6	.49	.53	15	1.4	26	31
107		14	1.8	.40	.48	4	1.2	.57	.58	14	1.6	16	18
112		10	1.4	.29	.31					10	2.1	10	12
117		14	2.1	1.46	1.88	13	1.6	.67	.75	14	3.9	186	433
	Mine B Areas												
1		25	2.0	.43	.53	8	1.7	.54	.60	21	1.9	70	86
2		20	1.7	.44	.59	4	1.3	.21	.22	20	1.7	67	79
	Conventional Section												
200		109	1.7	.50	.60	2	1.5	.66	.67	109	1.8	92	111
400		55	1.8	.50	.56	7	1.5	.35	.37	56	1.9	88	109
500		37	2.5	.51	.67					37	2.2	77	105
600		60	1.9	.42	.52					60	1.9	78	96
700		95	2.1	.43	.66	3	2.5	.75	.99	95	2.1	86	124
800		114	2.5	.30	.44	3	1.4	.31	.32	114	2.5	69	109
900		130	2.0	.37	.46	4	1.4	.13	.14	132	2.3	83	118
1000		63	1.7	.38	.44	5	1.6	.18	.19	63	2.2	80	108
1100		31	2.0	.38	.47	2	1.0	.32	.33	32	2.5	75	105
	Trackless Section												
5000		20	2.0	.69	.83	11	1.6	.71	.78	20	1.8	60	72
5100		17	2.0	.70	.77					17	2.0	86	98
6000		8	1.5	.65	.69	5	1.3	.45	.46	8	1.8	54	64
6200		28	2.6	.54	.74	3	1.3	.95	.97	28	2.3	80	101
7000		28	2.9	.78	1.10	14	1.8	.77	.90	28	2.2	80	107
8000		16	3.1	.60	.82	7	1.8	.76	.86	16	2.5	81	109

+ Many lighter samples were not analyzed for combustible dust and thus the means here cannot be compared to the total dust means.

* Excludes jobs and areas with less then seven samples.

Table 4. Job Breakdown Within Beats

Job	Samples in Beat Number							
	101	102	103	104	105	107	112	117
Driller J	5	4	5	4		2		
Driller LH						3	5	
Scooptram Op.	5	5	4	4	6			
Ore Truck Op.	3	7		4				
An/Fo Loader	1	4	3	4	5			
Rockbolter	4	4	5	4		5		
Conveyor Belt Op								13
1st Line Super.	5	5	5	4	1	4	5	1

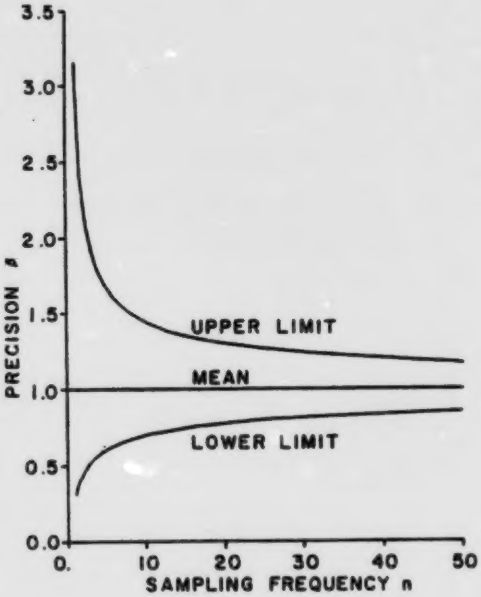

Fig. 1. Precision of the mean of n samples.

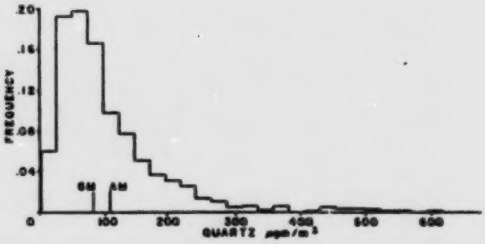

Fig. 2. Distribution of all samples on a linear scale.

same for the three dust assessments in both mines. The variance probably arises from a number of factors, which are only controlled within wide limits in the

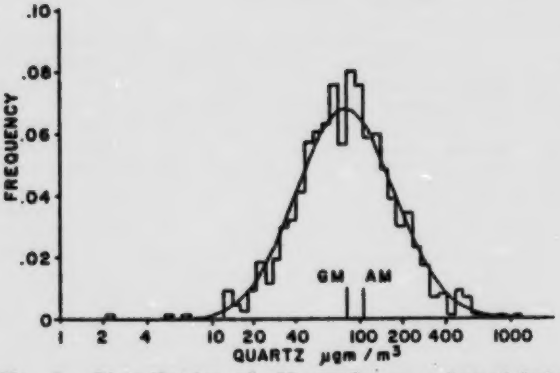

Fig. 3. Distribution of all samples on a logarithmic scale showing a good fit to a log-normal distribution (the smooth curve).

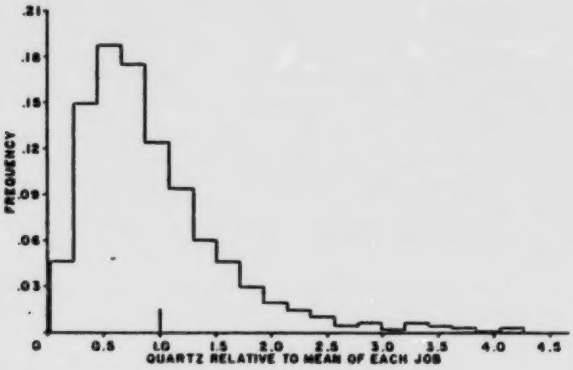

Fig. 4. Distribution of all samples divided by the mean of its respective job - linear scale.

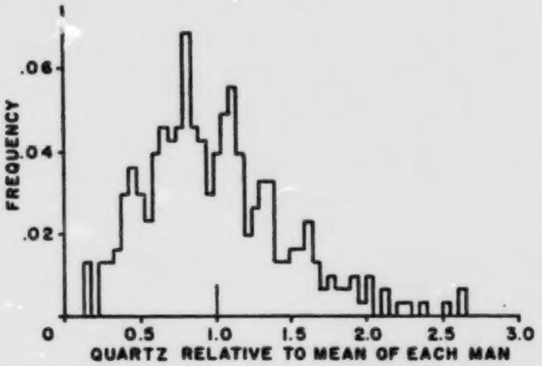

Fig. 5. Distribution of all samples contained in the sets consisting of men with three or more samples each divided by the mean of the respective man.

mining environment, as follows:

i) geological changes;
ii) drilling patterns and blasting, resulting in variable muck size;
iii) wetting;
iv) production;

v) tool condition;
vi) ventilating airflow.

This analysis showed that in these two mines the difference between the means of individual workers in each job is not significant. However, because of the small number of samples on each man and the high variability, differences as large as 50% could exist between their true means. There are significant differences between some jobs and between some areas.

This analysis has been conducted in mines in which dust control has been based on the konimetric assessments by number which indicate very different relative levels compared to gravimetric dust assessments. It is possible that the use of gravimetric sampling techniques with quartz assessment will alter some dust controls and lead to a reduction in the variability. However, there are still likely to be many poorly controlled variables remaining and a still substantial variability.

It is considered likely that similar variability occurred in all epidemiological studies on which existing dust standards have been based and that these, therefore, apply to the averages of groups over long periods of time rather than to measurements on individuals.

It is believed that full shift personal sampling is the best means available of assessing dust exposure in mines. Many samples on each person would be required to assess individual exposures. However, these results suggest that the job mean is a reasonable approximation to an individual's exposure.

Following Corn (12) it appears that each mine job can be classified as a uniform dust exposure zone on the basis of:

1) Work similarity - each job classification uses similar tools and does similar work.

2) Similarity with respect to hazardous agents - this is true for dusts, diesel gases and explosive fumes, but may not be so for radiation.

3) Environmental similarity - mine working places are generally similar throughout the mine and have similar average air flows. It has to be recognized that geometry is steadily changing in each mining place and that airflows can vary greatly. Possibly variations in intake air quality or airflow between sections in some mines could be significant leading to a zone definition of "job within section".

4) Identifiability - the job carried out by each man each day is normally well recorded.

It is suggested that dust sampling programs should be spread evenly throughout the year and cover nearly every man once in one or two surveys a year. To ensure that men are not exposed to excessive concentrations it is suggested that samples indicating more than twice the average value be repeated promptly, and appropriate action taken if the repeat is also high.

While effects of area may well be significant it is difficult to see it when so few samples are taken in each working place on each job. It is suggested that as ventilation is one major factor in dust control that working places be classified according to airflow and section intake air quality. The use of these criteria may make it possible to obtain weighting factors for improving the estimate of individual exposures from job means.

The major instrumental problem arising in this study was the switching off of dust samplers underground by the miners in the second mine. The problem was much less marked in the first mine. This appears to be a matter of support for the program by supervisory staff. In the first mine the samplers were first introduced to the mine captains, then to the first line supervisor in each beat and then to his men. In the second, relatively few samples were taken on first line and none on higher level supervisors, and some 45% of the samples had indicated running times of less than 90% of the period between switching on and off by the technician on surface. Some of these were due to accidental switching off (the switch guard is being improved), but most, it is believed, were deliberate. Many miners turned the samplers off in the lunch room, for instance. From the point of view of dust sampling it would be useful to use a key operated switch, but this would have the effect of decreasing the possible conservation of cap lamp battery life by a trapped miner.

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Section 5—Chapter 31

Comparison of Respirable Dust Specifications with Recent Lung Data

by

G. Knight and B. Kirk

American Industrial Hygiene Association Journal
43(8) pp575-579 (1982)

COMPARAISON DES NORMES EN MATIÈRE DE POUSSIÈRES INHALABLES AVEC LES RÉCENTES DONNÉES SUR LES POUMONS

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Le présent article vise à comparer les deux principales normes granulométriques en matière de poussières inhalables avec des modèles de poumons mis au point à partir des données d'une récente analyse. Pour ce faire, une simulation informatique est réalisée dans des nuages de poussière dont la granulométrie suit une distribution log-normale. Il en ressort que les deux normes reproduisent avec raisonnablement d'exactitude les modèles de poumon dont la respiration est faite soit par le nez ou la bouche dans des nuages de poussières industrielles habituelles; de plus, l'une ou l'autre pourrait, après légère modification, être utilisée comme limite de contrôle correspondante des poussières.

Am Ind Hyg Assoc J 43(8) 575-579

This paper compares the two major respirable dusts size specifications with lung models derived from a recent review using computer simulation in logarithmic normal dust clouds. It was found that either specification gives reasonable reproductibility with respect to either the nose or mouth breathing lung models over the usual range of industrial dust clouds, and either could be chosen as a standard with only a slight adjustment in the corresponding dust control limit.

Comparison of respirable dust specifications with recent lung data

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introduction

This paper forms part of the dust studies in CANMET in the Minerals Research Program of Energy, Mines and Resources Canada.

Two stage respirable dust samplers have been introduced to represent the split in dust deposition between the upper and lower respiratory tracts, because the major dust diseases, pneumoconiosis, are initiated by dust deposited in the lower tract, the pulmonary exchange or alveolar region, where dust clearance mechanisms are slow. Essentially the only dust which can be deposited here is that which can penetrate the upper tract.

Figure 1 shows the characteristics of dust behaviour in the lung after Hatch and Gross. Their discussion shows that:

1. Particles larger than 10 μm are essentially all removed in the upper tract and have little chance of reaching the alveolar region.
2. The efficiency of particle removal is high in the pulmonary air spaces, being essentially 100% down to around 2 μm. Below this size the deposition decreases to a minimum at 0.5 μm.
3. There are substantial variations in deposition with breathing pattern and between individuals.

Most two stage dust samplers intended to simulate deposition into these two regions of the lung have used a second stage with an efficiency close to 1 rather than the 0.4 maximum of the alveolar deposition curve and have not attempted to simulate the minimum of 0.5 μm. Thus some form of normalization is required to compare size selective dust samplers and the lung deposition curve.

Later experimental lung data was reviewed by Lippmann. Table I shows the data taken from the mean lines in his Figure G3 for nose and mouth breathing. Also shown are the two normalized lung models used in this study obtained from Lippmann's data by multiplying the two experimental curves by factors of 3.3 and 1.67 respectively, so that the maxima at about 2 μm are set equal to 1.

In this report these two lung models, nose and mouth breathing, are compared with the two major respirable size selection specifications used in the world. The (British) Medical Research Council (BMRC) produced a specification in 1952 based on the theoretical performance of a horizontal elutriator with a cut off chosen to give a best match to the lung data reviewed by Davies. This specification was adopted by the Johannesburg International Pneumoconiosis Conference in 1959. The second standard was originated by the U.S. Atomic Energy Commission in 1961 for radioactive dusts and was subsequently adopted in slightly modified form by the American Conference of Governmental Industrial Hygienists (ACGIH) in 1968.

The comparisons are made using a computer simulation following Lynch with a slight modification to the Los Alamos formula to meet the ACGIH specification as

$$P(D) = 1 - (D/2)^3/10 \quad \text{for } 0 < D < 2.8$$

The two lung models used straight line interpolation between the points listed in Table I. The comparison is carried out in dust clouds with a size distribution following a logarithmic normal law with mass median diameters (MMD) ranging from 0.2 to 30 μm and geometric standard deviations (GSD) from 1.5 to 2.0.

The integration was carried out in the 0 to 10, 2 to 10 and 3 to 10 μm size ranges. The latter two are used for comparison with the nose and mouth breathing lung models, respectively.

results

The results of the comparisons of the respirable dust size selection specifications with the two lung models are given in Table II.

1. The match between the size specification and the lung models is poor for the fine dust clouds and is substan-

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TABLE I
Alveolar Deposition for Nose and Mouth Breathing Following Lippmann

Aerodynamic Diameter	Penetrations Nose*	Penetrations [illegible]	Penetrations Mouth*	Relative Penetrations (at maximum = 1) Nose	Relative Penetrations (at maximum = 1) Mouth
0				1	0 54
0 15		26		0.85	0.43
0 2		224		0.74	0.372
0 3		202		0.67	0.335
0 4		195		0.65	0 33
0 5		213		0 70	0 354
0 6		224		0 74	0 372
0 7		24		0 79	0 40
0 8	246		258	0 82	0 43
0 9	258		291	0 85	0 485
1 0	264		303	0 87	0 50
1 5	291		386	0 96	0 64
1 75	-		---	0 99	---
2 0	303		48	1 0	0 80
2 5			---	0 99	---
2 8			---	---	0 99
3 0	291		60	0 96	1 0
3 25			---	---	0 99
4 0	202		54	0 67	0 89
5 0	101		336	0 33	0 56
6 0	.33		157	0 11	0 26
7 0	.11		067	0 04	0 11
8 0	0 0		022	0 0	0 04
9 0	0 0		013	0 0	0 02
10 0	0 0		007	0 0	0 01

*Following Lippmann Figure G3

tially improved by integrating only above the maximum deposition size of 2 or 3 μm.

2. The variation in ratio of dust collection by specification to lung model can be high.
3. Samplers of the BMRC specification collect more dust than those of the ACGIH specification in most dust clouds. In very fine dust clouds the two are equal and in very coarse dust clouds of low geometric standard deviations the ACGIH sampler can collect nearly twice as much dust.

discussion

The comparisons are summarized in Table III for the more usual industrial range of 2 to 10 μm in MMD and 2 to 3 in GSD. This table gives the maximum and minimum ratio, geometric range, median ratio of specification to lung model and mean ratios of specification to lung dust collection.

In terms of reproducibility in various dust clouds there is little to choose between the two specifications. The ACGIH specification is better in comparison with the nose breathing model, but worse over all in comparison with the lung depositions for both nose and mouth breathing.

The value of the median comparison between ACGIH specifications and BMRC specifications at 0.85 is a little higher than that of 0.81 suggested by Lynch.[(9)] However, this difference is due to the range of dust clouds included in the median as the individual values agree better than 2%. The difference between the two specifications should be considered in setting the TLV standard to be used.

In all laboratory and field comparisons we have carried out most 'respirable' dust samplers using nylon cyclones have collected substantially less dust in comparison to horizontal elutriators than indicated by the above studies

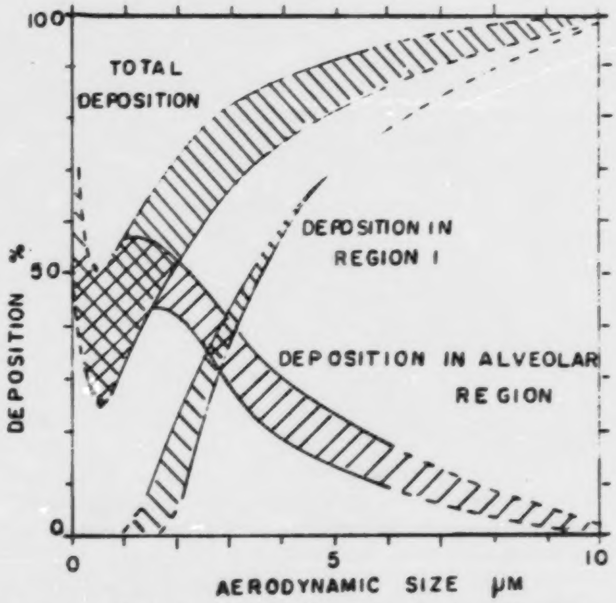

Figure 1 — Dust deposition in lungs showing range of variation between individuals and different breathing rates. After Hatch and Gross.[(1)]

TABLE II
Comparisons of Respirable Dust Specifications with Lung Models Given as the Ratio of 'Masses of Respirable Dust' Collected

MMD µm	Geometric Standard Deviation 1.5	2.0	2.2	2.4	2.6	3.0	1.5	2.0	2.2	2.4	2 6	3.0
	BMRC Nose breathing model integration range											
	0-10 µm						2 10 µm					
2	1 303	1 270	1 256	1 243	1 232	1 212	911	903	905	909	913	923
5	1 365	1 287	1 264	1 247	1 233	1 212	906	907	913	920	927	938
1 0	1 127	1 135	1 139	1 142	1 145	1 149	901	919	929	937	944	954
1 5	1 011	1 055	1 070	1 083	1 093	1 108	901	934	944	951	957	966
2 0	960	1 019	1 037	1 052	1 065	1 084	909	949	958	964	969	975
3 0	955	1 001	1 015	1 028	1 039	1 059	950	978	983	986	988	990
5 0	1 091	1 027	1 025	1 027	1 032	1 043	1 094	1 032	1 024	1 019	1 016	1 012
7 0	1 241	1 067	1 050	1 042	1 040	1 043	1 242	1 077	1 058	1 046	1 038	1 028
10 0	1 391	1 122	1 087	1 067	1 056	1 049	1 392	1 132	1 099	1 078	1 064	1 047
15 0	1 474	1 192	1 138	1 104	1 083	1 063	1 474	1 200	1 149	1 117	1 096	1 069
20 0	1 451	1 243	1 177	1 135	1 107	1 076	1 451	1 249	1 187	1 147	1 120	1 087
30 0	1 320	1 309	1 234	1 180	1 143	1 099	1 320	1 313	1 241	1 191	1 156	1 112
	BMRC Mouth breathing model integration range											
	0-10 µm						3 10 µm					
2	2 576	2 481	2 439	2 395	2 354	2 278	807	801	802	803	804	806
5	2 644	2 359	2 269	2 195	2 135	2 049	803	802	804	805	806	807
1 0	1 864	1 744	1 720	1 705	1 696	1 686	801	805	806	807	808	808
1 5	1 410	1 413	1 427	1 442	1 458	1 486	800	807	808	808	808	808
2 0	1 159	1 234	1 265	1 293	1 319	1 365	802	808	809	809	808	808
3 0	941	1 058	1 098	1 134	1 167	1 225	808	810	809	808	808	807
5 0	842	929	966	1 002	1 035	1 094	817	809	808	807	806	806
7 0	812	878	911	943	974	1 031	805	805	804	804	804	804
10 0	745	840	868	897	925	977	743	796	798	800	801	802
15 0	591	803	831	857	882	930	591	777	787	792	795	798
20 0	450	775	808	834	858	903	450	758	775	785	790	795
30 0	263	730	775	804	829	871	263	720	754	770	780	789
	ACGIH Nose breathing model integration range											
	0-10 µm						2 10 µm					
2	1 305	1 272	1 258	1 245	1 233	1 212	867	805	787	775	765	753
5	1 372	1 291	1 265	1 243	1 225	1 198	845	776	763	754	748	741
1 0	1 134	1 116	1 112	1 110	1 108	1 106	809	751	743	739	736	733
1 5	988	999	1 009	1 018	1 026	1 040	775	737	733	731	730	729
2 0	883	926	943	958	972	994	745	727	727	726	727	727
3 0	758	842	867	888	906	936	705	718	721	722	723	725
5 0	709	777	802	824	844	877	702	717	720	722	723	725
7 0	770	760	778	797	815	847	769	726	725	725	726	726
10 0	928	764	769	781	795	823	928	747	738	733	731	730
15 0	1 254	795	778	777	783	804	1 254	788	762	749	742	735
20 0	1 607	833	795	783	783	796	1 607	830	786	764	752	741
30 0	2 347	910	835	803	791	790	2 347	910	832	793	772	752
	ACGIH Mouth breathing model integration range											
	0-10 µm						3 10 µm					
2	2 579	2 485	2 443	2 399	2 357	2 277	572	537	529	524	520	514
5	2 659	2 366	2 269	2 188	2 122	2 026	560	526	520	516	513	509
1 0	1 877	1 715	1 680	1 656	1 640	1 623	546	517	509	509	508	505
1 5	1 378	1 338	1 345	1 356	1 369	1 395	534	511	508	506	505	503
2 0	1 067	1 121	1 150	1 178	1 205	1 252	523	507	505	503	503	502
3 0	746	890	937	980	1 018	1 084	507	501	501	500	500	500
5 0	548	703	756	803	846	920	489	496	496	497	497	498
7 0	504	626	675	721	763	838	486	493	494	495	496	496
10 0	497	572	615	656	696	767	493	491	492	493	494	495
15 0	503	535	568	503	538	704	503	491	491	492	493	494
20 0	498	520	546	576	507	568	498	492	491	492	492	493
30 0	468	508	525	548	573	527	468	493	492	492	492	493

The two major factors identified in our studies were the use of pulsating flows in early pumps - now eliminated and the use of plastic instead of metal filter holders with plastic leading to 25% lower dust concentrations. Metal filter holders on the nylon cyclone have given about 80% of the dust concentration from horizontal elutriator samplers

(BMRC specification). We note that most of the nylon cyclone size selection calibrations appear to have been carried out using metal filter holders and we have not found publications giving calibrations of the commercially produced American respirable dust samplers using nylon cyclones and commonly used 37mm plastic filter holder.

It appears to be a major advantage of the BMRC specification that a sampler can be built to it from drawings with reasonable accuracy and that other samplers can be adjusted to agree with it with reasonable reproducibility, by simple comparison tests in a laboratory or even an industrial dust cloud.

The approach of adjusting airflow to give the same indicated dust concentration probably gives greater reproducibility than does the use of an adjustment factor as developed for the U.S. coal mines.

In contrast any calibration to the ACGIH specification requires an arduous calibration using monodisperse dusts, and has not been carried out for many sampling trains used. No reference sampling train has been promulgated so that specific variations required for a specific analysis such as quartz can be checked. We have found that a horizontal elutriator with a top size cut of 5.8 μm gives reasonable agreement in laboratory tests and agrees with the ACGIH specification to within 6% in this computer simulation for dust clouds in the 1-10 MMD and 2-3 GSD range.

In hard rock mining quartz is the major health hazard and the airborne dust is often a mixture of mineral dust and fine particulates from the exhaust of a diesel engine. Those using the BMRC specification have developed personal samplers collecting about 50% more quartz with only 25% more fine diesel particulates than those developed using the ACGIH specification.(10, 11) Because of the high air flow resistance of the fine diesel particulates they tend to be the major limitation in collecting quartz, especially for the direct on filter XRD and IR techniques.(12)

conclusions

There is little to choose between the BMRC and ACGIH specifications in terms of reproducibility in assessing dust which could be deposited in the alveolar region in most industrial dust clouds. Apparently both are contained within the limits of human variability except for the maximum collection efficiency factor.

We plead for a uniform standard, as world wide as possible. In terms of the practical differences between the two specifications a compromise anywhere between the two is feasible. The advantages of the coarser end of the range is probably significant for many users of respirable dust samplers when both dust and fume are present, and analysis of dusts, such as quartz, are required.[12]

All existing samplers can be adjusted by change in flow rate to give reasonable reproducibility to either specification. Only on instruments, such as the Casella 113 gravimetric sampler is this troublesome in that the accurate very limited range flowmeter would have to be changed.

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TABLE III
Summary of Comparisons in Integration Range Above Maxima of Lung Deposition Curves

	Comparison Ratio to Lung Model				Ratio to Lung	
	Max	Min	Geometric Range	Median	Median	Geometric Range
BMRC Nose	1 132	949	1 18	1.01	3.3	2.8
BMRC Mouth	810	796	1 02	80	1.3	
ACGIH Nose	747	717	1 04	.73	2.42	2.9
ACGIH Mouth	501	491	1 02	50	.83	
ACGIH* / BMRC	908	681	1 33	.85	---	---

*Integration range 0-10 μm size

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3 June, 1981; Revised 8 March, 1982

Section 5—Chapter32

Workplace Respirable Dust Monitoring– Current and Proposed Canadian Practice

by

W. Bardswich, W.J. Campbell, G. Knight and E. Moore

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Vol. 2 pp1638-1644
International Labour Organisation. Geneva (1984)

SURVEILLANCE DES POUSSIÈRES INHALABLES SUR LES LIEUX DE TRAVAIL - MÉTHODES CANADIENNES ACTUELLES ET PROPOSÉES

INTRODUCTION

Tout programme de protection des travailleurs contre la pneumoconiose doit comprendre de nombreux paramètres liés aux poussières, notamment une technique acceptable d'évaluation de l'exposition cumulative du personnel aux poussières minérales.

Un cyclone métallique a été le principal instrument utilisé dans l'Étude des poussières dans l'ouest du Labrador (1) visant à évaluer les teneurs en poussières existantes.

Étant donné la variété d'instruments disponibles et le manque de consensus sur le choix de la technique d'échantillonnage, le programme initial a été modifié afin d'inclure l'étude d'un certain nombre d'appareils d'échantillonnage de poussières inhalables actuellement utilisés. Les résultats de l'étude ont permis de déceler les défauts de certains instruments et de constater le besoin d'établir un code uniformisé de surveillance des poussières.

WORKPLACE RESPIRABLE DUST MONITORING-CURRENT AND PROPOSED CANADIAN PRACTICE

INTRODUCTION

A program for the protection of workers against pneumoconiosis must comprise numerous dust related parameters including an acceptable technique for assessing personal cumulative exposure to mineral dusts.

A metal cyclone was the primary instrument used for the Labrador West Dust Study (1) for evaluation of existing dust levels.

Because of the variety of instruments available and the lack of consensus on the choice of sampling technique, the initial program developed was revised to include the study of a number of respirable dust sampling trains currently in use. The results of the study demonstrated the short-comings of some instruments and indicated the need for a uniform code of practice for dust monitoring.

DUST SAMPLING PRACTICES AT CANADIAN MINES

Although the gravimetric dust sampling technique was developed in the 1950's, it was not until the early 1970's that Canadian mining regulations began to reference gravimetric dust standards commonly referred to as the BMRC and ACGIH. Unfortunately, there was a lack of consensus in the various inspectorates on the choice of cyclone for the first-stage size selector. The metal cyclone, manufactured to BCIRA specifications and referred to as the HH cyclone, was designed to meet the BMRC criterion while the nylon (Dorr-Oliver) unit was specified for the ACGIH standard. Since the collection characteristics of these cyclones differ, the mass of dust collected also differed, thereby indicating the need for a double standard. The availability of various other models and designs compounds this problem. Current legislation in Canada recognizes both BMRC and ACGIH criteria, leading to some confusion.

SAMPLING TECHNIQUES IN LABRADOR WEST DUST STUDY (1)

a) Instruments

The four instruments used are listed in Table 1. A total of 8000 full shift dust samples were collected during the study of which 5500 were positional and [illegible]00 were personal. The metal cyclone was used for all positional and personal sampling for establishing existing dust levels.

A special experiment was a comparison of the four instruments listed in Table 1. They were compared on the basis of total respirable mass and respirable quartz, collected over 8-hour shifts, when samplers were positioned side-by-side at 68 fixed stations.

b) Quartz Analysis

The 8000 samples were analyzed at the Federal Government (CANMET) laboratories using direct-on-filter x-ray diffraction (XRD) with on-line computer. Some problems were encountered due to interference by other minerals making the analysis insensitive for the detection of crystobalite.

An inter-laboratory experiment comparing direct on-filter analysis and transfer-to-second filter analysis demonstrated good agreement between the two methods.(2)

The direct-on-filter XRD analysis for quartz gave adequate reproducibility on samples taken side-by-side, i.e., 95% of the samples had an error less than ± 0.01 mg. ± 10%.

c) Results

1. Overall analysis on the respirable dust concentration values indicated agreement between instruments HE, HH and CI (Table 1), while analysis indicated that the NC values were significantly different from the other three.

2. In particular, the analysis of variance technique was used to test the relative agreement of the four different sampling instruments. The significance of the equality of the means of each set of instruments was tested. At the 5% level, the hypothesis that the mean of the instruments, HE, HH and CI (Table 1) is the same may be accepted.
3. Furthermore, linear regression curves and coefficients of determination were calculated for respirable dust concentrations for all pairs of instruments and shown in Table 2. Good correlation of the three metal instruments, (HE, HH & CI) was obtained with respirable dust loadings in the range 0 to 2.5 mg. Above this limit, the instruments appeared to overload. The coefficient of determination (r^2) gives a measure of linear dispersion in readings between any pair of instruments. Any pair of instruments which includes the nylon cyclone (NC) gives a coefficient (r^2) for respirable dust concentration which is always less than the coefficient (r^2) for any other pair which excludes the nylon cyclone. Hence, based on linear dispersion, the nylon cyclone readings fluctuate more widely than the readings for any other of the four instruments.
4. Another method used to measure the variation of readings in the four instruments was to plot the histograms of the percent deviation from the mean of the HE, HH and CI instruments. The spread or dispersion of the histograms would then be a measure of the precision of the instrument. Figures 1-4 illustrate that the dispersion is comparatively low for the HE, HH and CI whereas the NC histogram has a much higher dispersion indicating less precision.
5. The results of the main sampling programs, using the metal cyclone, showed wide daily and seasonal variation for a specific location and/or occupation. Good correlation, however, was found

FIGURE 1

PERCENT DEVIATION, H & H CYCLONE

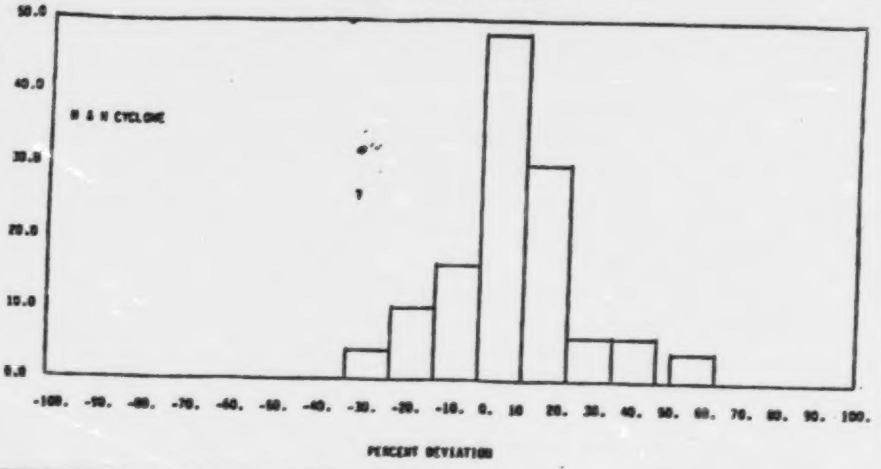


FIGURE 2

PERCENT DEVIATION NYLON CYCLONE

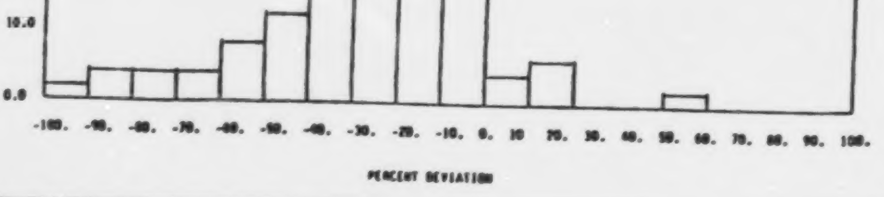


FIGURE 3

PERCENT DEVIATION CAMPEDS IMPACTOR

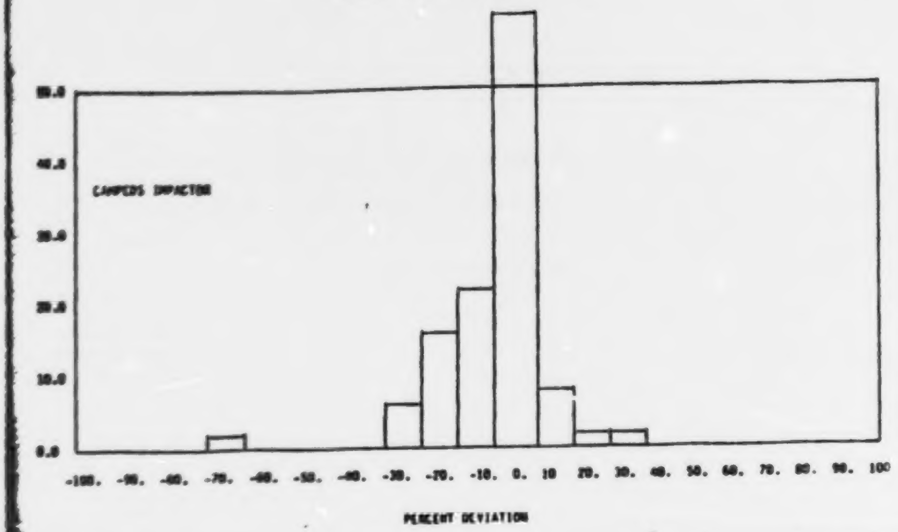
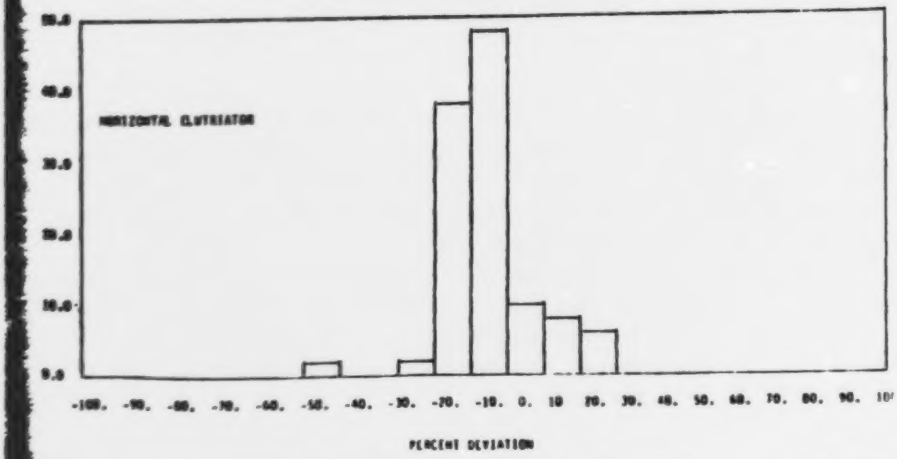


FIGURE 4

PERCENT DEVIATION HORIZONTAL ELUTRIATOR



between personal and positional sampling (*Figure 5*).

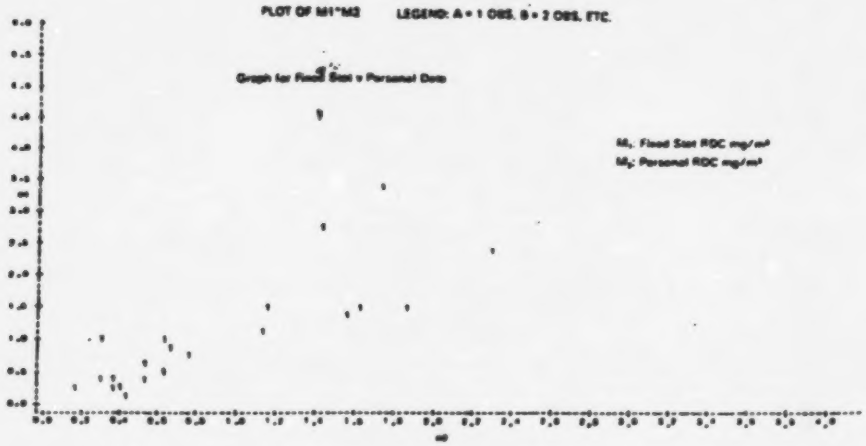


FIGURE 5

MEAN POSITIONAL DATA VS MEAN PERSONAL DATA
(GEOMETRIC MEANS BY LOCATION)

DUST LEVELS

a) Current Criterion: The "Threshold Limit Value (TLV)" as established by ACGIH, has been a controversial standard in Canadian mines. In particular, the criterion of 0.1 mg/m^3 of respirable dust has been challenged by industry spokesmen and the inspectorate have been hesitant in enforcing it.

b) Proposed Criterion: Pending resolution of the TLV issue, it is suggested that the establishment of "Dust Zones", with associated "Action Levels" is a concept worth pursuing. The proposal shown in Table 3 was included in the recommendation of the Labrador West Dust Study.

c) Merits of the Proposed Criteria:

  i) the "Dust Zones" and "Action Levels" may be accepted as an interim standard pending further investigation of existing dust standards.
  ii) management and workers are made aware of those working areas with increasing potential for injury to health.
  iii) the specific duties and responsibilities of management and workers are highlighted.
  iv) the frequency of dust sampling increases as the degree of hazard rises.
  v) the inspectorate is made aware of adverse working environments and is provided with plans for remedial action and a time schedule to monitor implementation.

CONCLUSIONS AND RECOMMENDATIONS

All instruments tested were acceptable, given the wide variations in dust levels and the precision of the analytical methods. The metal cyclone offered advantages in ease of operation and consistency of results.

The TLV formula incorporated in most legislation is difficult to interpret and monitor. There appears to be justification for the introduction of an "Action Level" approach to monitoring and control of dust levels.

Shift-long monitoring is required to approximate actual exposure of workers.

Personal sampling is desirable, but in many instances the more economical and dependable fixed station sampling can be used to produce reliable results.

The need for a uniform code of practice for monitoring respirable dust is the most significant conclusion of the Labrador West Dust Study, and of other Canadian studies and experiences.

Consistent, repeatable and reliable measurement of dust levels can be achieved by the use of good instruments, standardized sampling and analytical techniques, and qualified, experienced personnel. However, the maintenance of an acceptable working environment is dependent upon the tripartite cooperative efforts of inspectorate, management and worker.

The authors would like to acknowledge the assistance of the staff, technicians and consultants of the Labrador Institute of Northern Studies in the preparation of this presentation.

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TABLE 1

GRAVIMETRIC INSTRUMENTS USED IN STUDY

INSTRUMENT	FLOW RATE	FILTER MEDIUM	CRITERIA
HE: Horizontal Elutriator	1.88 ℓ/sec	25 mm, 5µm,Ag.	BMRC
HM: H & H Metal Cyclone	1.9 ℓ/min	25 mm, 5µm,Ag.	BMRC
CI: Casgada Impactor	2.0 ℓ/min	25 mm, 5µm,Ag.	BMRC
NC: Nylon Cyclone	1.7 ℓ/min	37 mm,0.8µm,Ag.	ACGIH

TABLE 2

REGRESSION CURVES & COEFFICIENT OF DETERMINATION (r^2)

INSTRUMENT (y)	REGRESSION EQUATION	COEFFICIENT OF DETERMINATION (r^2)	INSTRUMENT (x)
HM	$y=0.99x^{1.04}$	0.98	HE
HM	$y=1.07x^{1.05}$	0.98	CI
CI	$y=1.10x$	0.96	HE
NC	$y=0.73x^{1.2}$	0.86	CI
NC	$y=0.78x^{1.1}$	0.83	HE
HM	$y=1.50x$	0.79	NC

Table 3

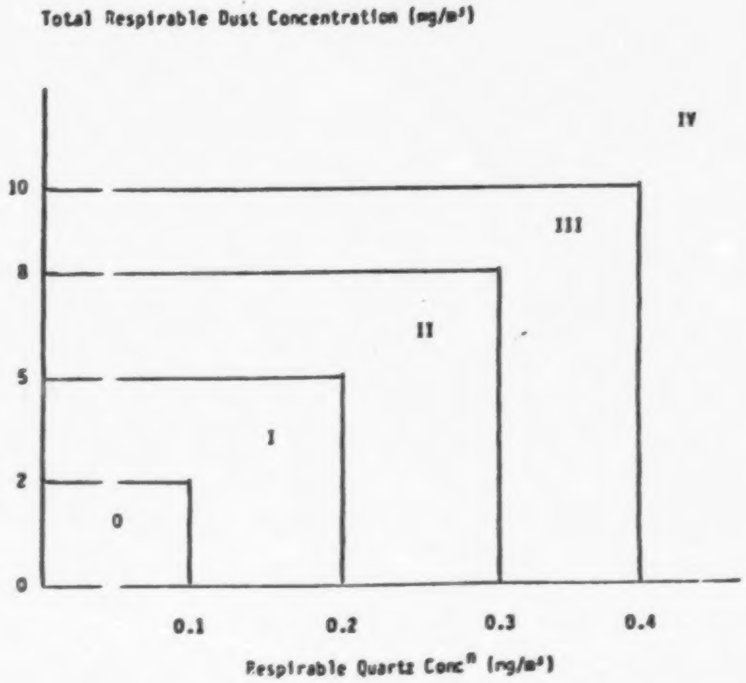
Zone Designations & Remedial Procedures

Zone Designation	Respirable Quartz Concentration (mg/m³)	Respirable Dust Concentration (mg/m³)	Remedial Procedures	Suggested Sampling Frequency
0	Less than 0,1 mg/m³	Less than 2 mg/m³	Zone	Each station to be sampled semi-annually: at least one station every 30 days
I	Greater than 0,1 mg/m³ Less than 0,2 mg/m³	Greater than 2 mg/m³ Less than 5 mg/m³	Monitor for dust sources and take corrective action as required	Each station tp be sampled quatemly, at least one station every 30 days
II	Greater than 0,2 mg/m³ Less than 0,3 mg/m³	Greater than 5 mg/m³ Less than 8 mg/m³	Company to submit plans for corrective action. Corrective action to be implemented by Inspector's order. Dust masks optional	Each station to be sampled once every thirty (30) days
III	Greater than 0,3 mg/m³ Less than 0,4 mg/m³	Greater than 8 mg/m³ Less than 10 mg/m³	Company to immediately report occurrence to Inspector, and submit plans for corrective action within 7 days. Corrective action to be implemented by Inspector's order. Dust masks are mandatory and area to be posted as such	Each station to be sampled once every two weeks
IV	Greater than 0,4 mg/m³	Greater than 10 mg/m³	See text	See text

(All levels based on H & H cyclone data)

Table 4

ZONING CLASSIFICATION



(All levels based on M & M Cyclone Data)

Section 5—Chapter 33

Rock Fibre in Nonasbestos Mines — A Suggested Program for Canadian Mines

by

G. Knight

in Definitions for Asbestos and other Health-Related
Silicates. Edited by B. Levadie. pp184-187
ASTM Special technical publication 834:
ASTM Philadelphia (1982)

FIBRE ROCHEUSE DANS DES MINES D'EXTRACTION DE MINERAI AUTRE QUE L'AMIANTE - PROGRAMME PROPOSÉ POUR LES MINES CANADIENNES

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Un programme de détection et d'évaluation des fibres d'amiante et d'autres fibres rocheuses en suspension dans l'air des mines est présenté. Il est brièvement question d'une interprétation des résultats et des difficultés liées à l'application des normes dans l'industrie de l'amiante. Les principaux problèmes concernent l'évaluation des fibres lorsque leur teneur est faible par rapport aux particules totales et le manque de connaissance sur les dangers que représente la présence de fibres de longueurs et de diamètres différents. C'est pourquoi il est difficile de comparer ces concentrations avec celles contenues dans des normes principalement élaborées en fonction des conditions prévalant dans les usines textiles de l'amiante.

Geoffrey Knight[1]

Rock Fiber in Nonasbestos Mines—A Suggested Program for Canadian Mines

REFERENCE: Knight, G., "**Rock Fiber in Nonasbestos Mines—A Suggested Program for Canadian Mines,**" *Definitions for Asbestos and Other Health-Related Silicates, ASTM STP 834*, Benjamin Levadie, Ed., American Society for Testing and Materials, Philadelphia, 1984, pp. 184–187.

ABSTRACT: A program is given for the detection and assessment of airborne asbestos and other rock fibers in mines. An interpretation of the results and the difficulties of applying asbestos industry workplace standards are discussed briefly. The major problems are the assessment of fibers when present as a low proportion of the total particles, and the lack of knowledge of the degree of hazard of fibers of different lengths and diameters, which leads to difficulty in comparing these fiber concentrations with those of standards developed mainly in asbestos textile workplaces.

KEY WORDS: health-related silicates, asbestos, rock fibers, nonasbestos mines, airborne asbestos, health hazard, mine survey

Asbestos fibers are recognized as a serious health hazard if inhaled in quantity, possibly leading to asbestosis, lung cancer, and mesothelioma.

It is recognized that many mines with ores other than asbestos may have asbestos minerals in noncommercial quantities or qualities and that precautions have to be taken to prevent excessive exposure of workers. It is also recognized that nonasbestos rock fibers can be present, as has been suggested to be the origin of the high mesothelioma incidence in the Cappadocia region of Turkey. Some 150 minerals that can occur in fibrous forms have been recognized [*1*].[2]

The major problems in making decisions on the control of rock fiber are the nonspecificity of the measurement methods and the fact that the standards used in the workplace (usually 0.2 to 5 fibers/mL, using the optical microscope/membrane filter method) are only appropriate for the length and diameter distributions and the composition of fibers found in the asbestos industry, mainly in textiles and milling, where these standards were derived. Their extension to other industries and mineral fibers presents difficulties because of the inadequate data available on the characteristics, length, diameter, and composition of the type of fiber that leads to health hazards. Pott's hypothesis is one starting point [2], and the effect of the composition on the fiber's solubility in body fluids, particularly insofar as it affects the residence time, is a second. Pott's hypothesis suggests that the most hazardous fibers are 10 to 50 μm in length and less than 1 μm in diameter, with the hazard decreasing for shorter or fatter fibers. No line has been drawn as to where the decreasing hazard balances the increasing number of shorter fibers. This leads to problems in measurement in that, particularly in asbestos, a substantial proportion of these fibers may have diameters below the limit of visibility of optical microscopes, and the longer fibers are usually underestimated in electron microscopy. Thus any estimate of the relative hazard from fibers determined by counting is subject to the possibility of large error when the standard methods are used.

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[2] The italic numbers in brackets refer to the list of references appended to this paper.

Further problems are the detection and counting of fibers in the presence of much higher concentrations of other minerals than is common in the asbestos industry, and distinguishing fibers from acicular particles. It has been suggested that, for these reasons, the second set of counting rules given in the International Standards Organization draft optical microscope method[3] is more suitable than the first set, which is similar to those used in most jurisdictions.

These counting rules (the second set) use a 5:1 aspect ratio and count the ends of all fibers in which the end is 5 μm or more in length, regardless of whether the other end is attached to a particle, bundle, or other form. These rules are compatible with the World Health Organization (WHO) recommendations for man-made mineral fibers [*3*] while the other set is not.

Suggested Canadian Mine Survey Program

Stage 1

The areas in Canada in which asbestos-mineral-bearing rocks could be found were examined by the Geological Survey of Canada.[4]

Stage 2

It is proposed that membrane filter samples be collected at crusher stations and similar dusty sites where there is a mixture of the ores and waste rock and that these samples be assessed by optical microscopy. Mines found to have significant numbers of fibers, more than about 0.5 per millilitre, should be examined further.

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[3] "Determinations of Airborne Inorganic Fibre Concentrations in Workplaces by Light Microscopy (Membrane Filter Method)," Draft ISO/DIS International Standard, International Organization for Standardization, Geneva, Switzerland, November 1982.

[4] Unpublished report, Geological Survey of Canada, Ottawa, Canada.

Stage 3

It is proposed that mine geologists and other responsible personnel be requested to report zones containing possibly fibrous minerals and collect rock samples for evaluation. The expectation is that this program will only detect asbestos veins; however, at one iron ore mine fiber was reported because it was causing clogging in the beneficiation process. The collected rock specimens should be examined by petrological and possibly electron microscope techniques.

Stage 4

It is proposed that more complete surveys of airborne fibers in the mines be carried out.

Stage 5

In mines with a possible hazard, indicated by fiber counts or fibrous mineral identification, it is necessary to characterize the fibers and assess their probable health effects so that a suitable control level can be chosen. This is necessary even for asbestos exposure, as the standards range from 0.2 (crocidolite) to 5 fibers/mL (Quebec chrysotile mines and mills).

Discussion

To date in Canada, Stage 1 has been completed, but the report has not been published. Stage 2 has been carried out nonsystematically by various uncoordinated organizations. There have been no reports of fiber levels sufficient to require progress to a further level. In the course of an epidemiological study in one iron ore mining region, the possibility of fibrous exposure was raised through Stage 3 (mine personnel reports) and through the appearance of lower-zone irregular opacities on medical lung X-rays, which is common in asbestosis but not in silicosis.

In this study, the following multipronged attack was developed to examine the possible fibrous rock dust problem.[5]

1. An airborne fiber concentrations survey was conducted using the standard optical microscope membrane filter method.
2. Special, long-term (days) samples of airborne fibers were collected for characterization by electron microscopy.
3. A survey of present and past use of asbestos (insulation, packings, and other uses) was made in the plants.
4. An examination was made of mine and other geologists' reports on the region.

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[5] "West Labrador Mixed Dust Study," Ministry of Mines, Newfoundland and Labrador, St. John, N.B., Canada, 1982.

5. A geological survey was made and rock specimens were collected from exposed faces in the open pits, using a grid pattern and stratification.

6. Mineralogical characterization of these specimens was then carried out.

7. Specimens showing possible fibrous minerals were crushed and characterized by electron microscopy.

The results of the measurements suggested that the fibers present were nearly all less than 5 μm in length and thus, by both the standard method and Pott's hypothesis, under control. The airborne fibers, however, were not similar to airborne asbestos fiber in size distribution, and the composition was different. This exemplifies the difficulties of assessing the potential hazard and the appropriate control level.

Control methods can be the standard control of airborne dust emissions; however, because the fibers may occur mainly in particular strata, it may be possible to avoid mining those strata with little loss of ore or increase in costs when driving in waste rock. In the iron ore mine in which fibers caused clogging in the beneficiation program, the particular stratum was thereafter treated as waste rather than ore. This stratum, however, is believed to be thin and more friable than the adjacent ore zone, and a higher recovery might be obtained by passing the material from that zone over a grizzly screen and rejecting the fines.

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[2] Pott, F., "Some Aspects on the Dosimetry of the Carcinogenic Potency of Asbestos and Other Fibrous Dusts," *Staub-Reinhaltung der Luft*, Vol. 38, December 1978, p. 486.

[3] "Methods of Monitoring and Evaluating Airborne Man-Made Mineral Fibers," report on WHO Consultation, Copenhagen, 29 April–1 May 1980, Regional Office for Europe, World Health Organization, Copenhagen, 1981.

5. 34

Section 5—Chapter 34

Letters on Alveolar Dust Deposition

Annals of Occupational Hygiene 1982-1986

DEFINITIONS OF ALVEOLAR DUST DEPOSITION AND RESPIRABLE DUST SAMPLING

Sir,

Both IOS (1983) and ACGIH (1984) have produced recommendations for dust sampling to define deposition in the respiratory tract. Both recommendations are inconsistent with respect to alveolar dust deposition and respirable dust sampling. This is shown by the statement by PHELAN (1984a): 'The three sampling efficiency curves used to describe IPM (inspirable particulate mass), TPM (thoracic particulate mass), and RPM (respirable particulate mass) cannot be subtracted from one another in order to define deposition within an anatomic region'. This demonstrates that the purpose 'to recommend size selective aerosol sampling procedures which will permit reliable collection of aerosol fractions which can be expected to be available for deposition in the various major subregions of the human respiratory tract', as stated by PHELAN (1984b), is not fully met.

An improvement to this position could be obtained by returning to the original separate concepts of alveolar deposition and respirable dust sampling as they were explained to me in the 1950s by my former colleagues, R. J. Hamilton and W. H. Walton. The alveolar deposition peaks at about 40% at 2 μm aerodynamic particle size, whereas two-stage dust samplers use a high efficiency filter as the second stage and the shape of the respirable sampling curve was obtained as a best match, in the 2 to 10 μm region, to the curve obtained by multiplying the alveolar deposition curve by a factor of about 2.5, such that it reached 100% at its maximum.

Thus the recommendations to these two committees are that they should:

(1) separate the concepts of 'respirable dust sampling' from that of 'alveolar deposition';
(2) select consensus alveolar deposition curves that represent mean realist human behaviour similar to those of the TASK GROUP ON LUNG DYNAMICS (1966);
(3) specify that scaling factors (SF) are to be used to relate respirable dust sampling specifications to mean alveolar deposition (AD);
(4) state that the mean anatomic regional depositions can be obtained with a reasonable degree of accuracy by manipulating IPM, TPM, and AD (RPM/SF).

KNIGHT and KIRK (1982) have demonstrated computer simulation techniques for determining scaling factors for the two respirable dust sampling specifications of BMRC (1952) and ACGIH (1968). Values of 3.46 and 2.90 can be derived from their tables to relate to the mean nose breathing curve as reviewed by LIPPMANN (1979). These are the means for 1.5 to 10.0 MD and 2.0 to 3.0 GSD values in the 0 to 10 μm integration.

This approach would have two major advantages. Firstly, it would enable the allowable size selection tolerances to be corrected between types of instruments by choice of an appropriate scaling factor and avoid the difficulties that would be found in applying standards with different instruments. Secondly, it would permit the optimization of the dust sampler to the specific problem. For instance, in hard rock underground mines, the main problem is often assessment of quartz in the respirable size range in the presence of up to 90% of fine particulate from diesel engine exhausts. KNIGHT has developed a direct-on-filter X-ray diffraction analysis technique for respirable quartz. The sensitivity and reproducibility of their method improves with increasing mass per unit area. It can be shown that, when the filter size and airflow are optimized for the available battery powered personal sampling pumps, the use of BMRC size selection specification permits a 50% greater quartz density than that of the ACGIH (1968).

The introduction of a sampling concept to distinguish between contaminated dusts and finer particulates, smokes and fumes, would be useful for anatomical understanding, both because of the exhalation of some of the fine particulate and because of the sometimes substantial differences in solubility. I have found that size selective impactor samplers with cuts in the 1–2 μm range increase the proportion of diesel exhaust particulate as compared to mineral dust.

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RATIONALE OF ACGIH RECOMMENDATIONS FOR SIZE-SELECTIVE SAMPLING

Sir,

The members of the ACGIH Technical Committee on Air Sampling Procedures wish to respond to the Letter by Geoff Knight (*Ann. occup. Hyg.* **29**, 526–528, 1985).

Knight criticizes a report of the American Conference of Governmental Industrial Hygienists Technical Committee on Air Sampling Procedures (ACGIH, 1984), which is developing guidance for particle size-selective sampling in the workplace. The committee report includes collection efficiency specifications for three types of particle size-selective samplers and guidance for the development of TLVs (threshold limit values) with which the airborne mass concentrations measured by the samplers could be compared. Knight objects to the committee's approach because it does not include estimation of the airborne mass concentration of particles which would be expected to deposit in the various regions of the respiratory tract. He suggests that 'the mean anatomical regional depositions can be obtained with a reasonable degree of accuracy' from linear combinations (adding, subtracting and scaling) of the three sampler results and recommends that the committee adopt such calculations (the 'regional dose' approach). The Committee recognizes that specifications for the particle size-selectivity of samplers can be guided by one of at least two alternative conceptual bases: one focuses on regional deposition and the other on regional exposure. After discussing both, the Committee adopted the regional exposure approach which focuses on the particles which would be expected to *enter* (be available for deposition in) a respiratory tract region rather than those which would be expected to *deposit* there.

The committee defined three major regions of the respiratory tract: the head airway; tracheobronchial; and gas exchange regions. The airborne mass concentration measured by an IPM (inspirable particulate mass) sampler approximates the mass concentration of particles which would be expected to pass the lips or nares, based on available inspirability data for a normal range of wind velocities and orientations. The airborne mass concentrations measured by the TPM (thoracic particulate mass) and RPM (respirable particulate mass) samplers approximate the mass concentrations of particles which would be expected to pass the larynx and the ciliated airways, respectively, based on available data on deposition in the head airway and tracheobronchial regions. Although it seems that size-selective sampling should be based on regional deposition since deposition determines the direct regional dose (regional dose approach), the committee noted several advantages and no serious disadvantages to the regional exposure approach. Recommended particle size-selectivity specifications were guided by the principle that each sample should approximate the airborne mass concentration which enters (exposes) one of the three regions of the respiratory tract. Some of the points which were considered by the committee are given below.

(1) The committee's recommendations for size-selective sampling in the workplace are based on the concept that valid evaluation of potential airborne particulate hazards excludes those particles too large to significantly contribute to the health effect of concern. This concept is already incorporated into ACGIH and BMRC definitions of respirable dust which exclude particles considered too large to penetrate to the gas exchange region. Current 'total dust' sampling excludes, perhaps unintentionally, particles too large to enter the sampler.

(2) One problem with the regional dose approach to size-selective sampling is that particles which pass through a region but are not expected to deposit under normal conditions (generally the smaller particles) are excluded from the hazard evaluation. While it is desirable to accurately estimate dose by including such considerations in laboratory experiments and epidemiological studies, the committee feels such an approach is not proper for hazard evaluation. In spite of the data acquired in the last three decades on deposition of aerosols in humans under a variety of conditions, it is not possible to accurately predict the dose delivered to a particular worker in his or her workplace. Complications arise owing to such causes as individual variability, work rate, breathing pattern, abnormal health, particle charge and particle hygroscopicity. Given this uncertainty, the committee does not feel it is prudent to exclude from consideration in a hazard evaluation that mass of airborne particles which would enter but not normally deposit in a region where its adverse effect could be exerted.

(3) Compared with the regional dose approach, the Committee's regional exposure approach tends to include smaller particles in a sample intended to evaluate hazard to a particular respiratory tract region. The economic impact of this approach is relatively small, because where both exist the larger particles generally dominate the mass concentration.

(4) Measurement of 'total dust' concentration is a widely accepted concept in dust sampling for hazard evaluation. This concept is not based on any human deposition information. The collection efficiency specifications of the IPM sampler essentially clarify the measurement of 'total dust' concentration and remove current ambiguities arising from the use of several samplers which have different (and often unknown) collection efficiency characteristics.

(5) Knight states that the collection efficiency curve for respirable dust is derived from data for deposition in the gas exchange region with the introduction of a scaling factor. The definition adopted by the committee is essentially a clarification of the previous ACGIH definition and happens also to be consistent with data for the fraction of inhaled particles which may be expected to enter the gas exchange region. Thus, the definition of respirable dust is retained in the committee's recommendations and is consistent with its approach to size-selective sampling.

In summary, the committee considered and rejected the regional dose approach to airborne particle sampling for hazard evaluation and adopted the regional exposure approach which it considered simpler, more reliable, protective of more workers and whose conceptual basis is consistent with current practice. With these considerations in mind, the committee recommends future size-selective sampling based on its sampler definitions (ACGIH, 1984; PHALEN *et al.*, 1986).

Knight also made a point that it is often valuable to have a sampler with a cut-point around 1–2 μm to distinguish between finer particulates and dusts. The committee's recommendations do not preclude such a sampler but only specify the net collection efficiency of a sampler or combination of samplers used for health hazard evaluation.

The ACGIH Technical Committee on Air Sampling Procedure appreciates this opportunity to clarify its work and welcomes written comments and suggestions. The Chairman's address is:

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* * *

AUTHOR'S REPLY

Sir,

Dr. Soderholm defends the position of the ACGIH Committee very well. However, he does not recognize the cost. One particular point made in my letter (*Ann. occup. Hyg.* 29, 526–528) is not recognized in his point (3). The inclusion of fine diesel particulate is a cost in sampling for quartz dust in mines.

The other major point I was trying to make was an approach that would permit 'respirable' or other dust sampling instruments with a range of size selection mechanisms and specifications to suit specific sampling requirements, such as continuous monitors (optical size selection for instance) and special analytical techniques with the use of appropriate scaling factors to correspond to ACGIH, BMRC or alveolar deposition obtained by calculation or calibration. This has been the practice in the U.S. coal mines where the law specifies the Casella NCB MRE 113A horizontal elutriator as the reference sampler but, for convenience, and the nylon cyclone sampler is used with an experimentally determined scaling factor (TOMB *et al.*, 1973).

The tendency to legal enshrinement of a particular sampler without outlining acceptable methods of calibrating and scaling other sampling systems stultifies development and at present is resulting in the use of the nylon cyclone sampler in Ontario hard rock mines where quartz dust levels are frequently below its useful range instead of the sampling system developed for Canadian hard rock mines which collected twice as much quartz dust (KNIGHT, 1986). A further developed sampler collects four times as much dust with corresponding increases in precision.

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DIFFERENCES BETWEEN ASBESTOS FIBRE SIZE DISTRIBUTIONS IN AIR AND IN THE LUNG

Sir,

Hwang and Gibbs (1981) discuss very briefly the effect of lung deposition in comparing airborne size distributions and lung size distributions of asbestos fibre. I would suggest that the discussion overlooks one possibly very important factor in lung deposition. Coarse particles and fibres breathed in are deposited totally within the body and their suggestion that some long fibres are deposited in the upper tract and lost to the measurements made by Pooley and Clark (1979) is probably correct. However, it is also usually accepted that a large proportion of the finer dust is present in the exhaled air and some is deposited in the airways by diffusion and would thus also be lost to the lung measurement. The shape of fibres is likely to reduce the diffusion coefficient and the total deposition, thus the difference between the size distributions measured in the lung (Pooley and Clark, 1979) and those in the air (Hwang and Gibbs, 1981) may reflect the size selection of the fibre deposition mechanisms as well as that of the clearance mechanisms.

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LISTING OF PAPERS : Section 6 . General

6.35

Section 6 - Chapter 35

Mines Branch Dust Laboratory

by

G. Knight and T. S. Cochrane

Canadian Mining Journal 88 (10) 79-82 (1967)

Laboratoire d'études des poussières, de la Direction des mines

par G. Knight et T.S. Cochrane

Résumé - La fonction essentielle du Laboratoire d'études des poussières, à la Direction des mines, est de compléter les connaissances actuelles dans le domaine de la mesure, de la production et de la dispersion des poussières. Les premières recherches entreprises ont pour but l'établissement expérimental des critères qui permettront de définir dans une mine un nuage de poussières aériennes. Dans les études en cours, on considère les trois principaux paramètres d'une nuée de poussières : la concentration, la composition et la distribution granulométrique de ces poussières. On examine actuellement l'information disponible sur le mécanisme de production des poussières et sur les relations existant entre le caractère de la roche et les taux de poussières. On réalise actuellement ces études dans le cadre des projets suivants : (1) la comparaison et l'évaluation des instruments de collecte des poussières; (2) les analyses de la composition des poussières aériennes; (3) la distribution granulométrique des poussières; et (4) la documentation sur la nature de la roche et sur les relations entre le caractère de la roche et les taux de poussières.

Mines Branch Dust Laboratory

G. KNIGHT[1] & T. S. COCHRANE[2]

■ The work of Mines Branch in the area of mining research is directed towards reducing costs, increasing safety and providing information that will assist in improving environmental conditions.

In 1960 a review of the status of the airborne dust problem in mines was made from which it was concluded that the mines have been able to keep most of the pneumoconiosis problems under control. However, to improve environmental conditions and hence meet the competition of other industries for labor, it was considered helpful to have greater knowledge of the physical properties of dust and of the response of measuring instruments. Once these basic data were available, sampling instruments could be selected to match the conditions and used with greater confidence.

The primary function of the Mines Branch Dust Laboratory is to complement existing knowledge in the field of measurement, production and dispersion of dust. In line with this function, the initial investigations undertaken are to assist in establishing experimentally the criteria for defining an airborne dust cloud in a mine. Current studies involve a consideration of the three main parameters of a dust cloud: concentration, composition and size distribution. In addition, available information on the mechanism of dust production and the rock-dust relationships is being reviewed. These studies are implemented under the following project designations and in the following order of priority as personnel and resources become available:

1. Comparison and evaluation of dust sampling instruments.
2. Compositional analysis of airborne dusts.
3. Size distribution of dusts.
4. Rock documentation and rock-dust relationships.

At the outset it was considered impractical to carry out studies in the field because of the variability of conditions and the numerous interfering factors met with underground. For the purpose of creating, maintaining, and controlling dust clouds of known characteristics, a small scale dust chamber was constructed at the Mines Branch, Ottawa (1961). A discussion of the many problems overcome and the time involved in acquiring satisfactory test conditions in the chamber and in adapting dust sampling instruments for remote control operation is beyond the scope of this paper. During the interval 1962 to 1964 the chamber was calibrated and initial test runs made. In early 1965 the Dust Laboratory was transferred to Elliot Lake as part of the Mining Research Laboratories. Following recalibration of the chamber the experimental studies were resumed in the summer of 1965.

Basically the dust chamber, shown in Figure 1, consists of three main components: the test chamber, the dust feed unit and the dust dispersal mechanism. The test chamber is a rectangular sheet metal lined structure 6 feet high, 6 feet wide and 8 feet long (288 cubic feet), fitted with an air tight door and two observation windows. The dust feed unit (1) consists of a two speed rotating plate with grooves of five sizes, fed with dust from a hopper and a scraper. This gives dust feed rates from 1 to 1100 cubic centimeters per hour. Dust concentrations from 100 to 100,000 particles per cubic centimeter (3 to 3000 million particles per cubic foot) have been produced in the test chamber. Three mechanisms of dust dispersion into the chamber intake air (15 - 20 changes per hour) have so far been used:

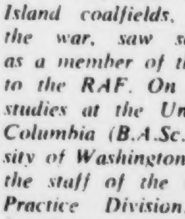
(a) a compressed air ejector (1);
(b) a rotating plate pulveriser preceded and followed by air ejectors;
(c) a compresser-air-operated, twin-jet fluid energy mill.

Research projects

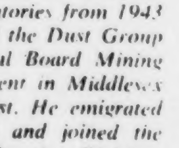
Comparison and evaluation of dust sampling instruments

The object of this research is to compare and evaluate a wide range of dust sampling instruments. Among the factors to be considered in this evaluation are:

(a) The variability with which a dust sampling instrument estimates the dust concentration present in the air.
(b) Performance of dust sampler and method of assessment in measuring concentration of fine dust particles and their relationship to the health hazard.
(c) Performance of method used to avoid assessment of the coarse



Thos. S. Cochrane was born in Scotland in 1918. Emigrated to Canada in 1923 and received primary and secondary education in British Columbia. From 1936 to 1940 he worked with Canadian Collieries (D) Ltd. in the Vancouver Island coalfields, B.C. and during the war, saw service in Europe as a member of the RCAF attached to the RAF. On completion of his studies at the University of British Columbia (B.A.Sc.) and the University of Washington (M.Sc.), he joined the staff of the Fuels and Mining Practice Division, Mines Branch, based in Crowsnest Pass, Alberta. From 1951 to 1959 he was engaged in ground control studies in Western Canada. In 1959 he transferred to Ottawa and carried on studies both in ground control and dust research as a research engineer. In 1964 he became manager of the Mining Research Laboratories at Elliot Lake, Ontario.



Geoffrey Knight, B.Sc., A. Ins. P. was born in Oxfordshire, August 17, 1927. He received his early schooling in private schools in England and graduated from the University of London in 1946. He was a research assistant at the Kodak Research Laboratories from 1943 to 1953, then joined the Dust Group of the National Coal Board Mining Research Establishment in Middlesex as a research scientist. He emigrated to Canada in 1965 and joined the Fuels and Mining Practice Division, Mines Branch, Elliot Lake. His present position is research scientist in charge of the Dust Research Laboratory at the Mining Research Laboratories.

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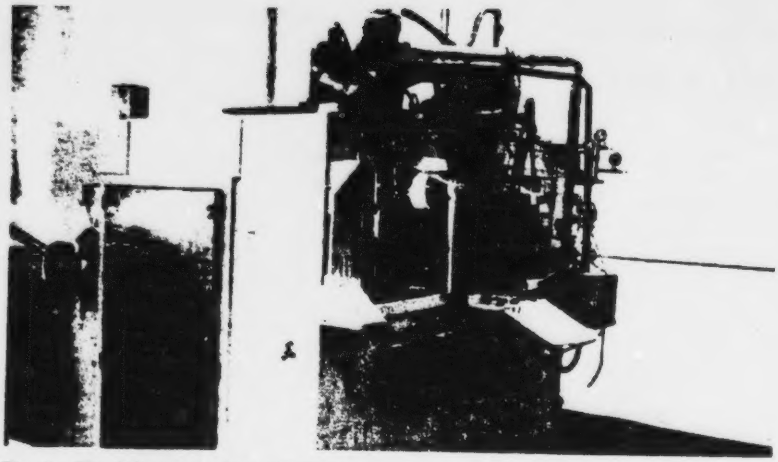

Fig. 1—**The laboratory** dust chamber

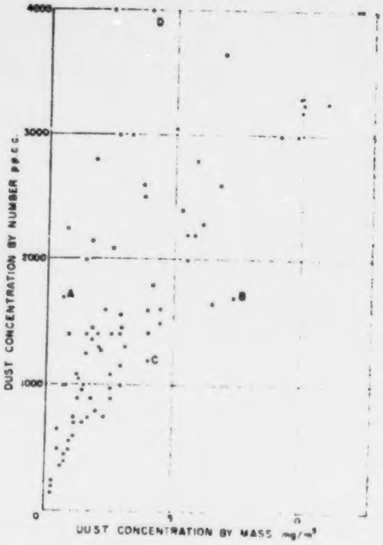

Fig. 2—(right) **Comparison of dust** concentrations measured by the Konimeter and the Hexhlett (six types of dust and four size distributions)

dust that is not a pneumoconiosis hazard because of its collection in the nose and bronchial passages.

(d) The property of the dust measured: mass, number, light scatter or other and its relationship to medical recommendations.

(e) Time and skill required to operate dust sampler and assess sample.

Another factor which should be considered by those responsible for dust sampling is the purpose of the sampling, either for dust control or for estimation of health hazard. Sampling for dust control is related to the particular operation, on the other hand the health hazard is concerned with the dust concentrations over years. It is recommended (2): that the mean dust concentration over a long period, such as a shift, should be used as a single parameter for health hazard; and that it is desirable to record peaks of exceptionally high dust concentration. These peaks are likely to occur regularly only when high powered mining machines are used for short periods at a time.

In the first part of this research program the dust sampling instruments, described in Table 1, have been used to measure concentrations of non-aggregated dust clouds prepared from five pure minerals and glass fibre using four methods of dust dispersion. The materials chosen were coal, silica and pyrite to examine the effect of particle density; silica, mica, asbestos and glass fibre, to examine the effect of particle shape. The four methods of dust dispersion gave dust clouds covering a range of size distributions with only small numbers of aggregated particles.

In Figure 2, a scatter-diagram of dust concentrations is shown as measured by the Konimeter and the Hexhlett over a range of fine to coarse dust clouds. Each plotted point represents the two measurements taken simultaneously in one particular dust cloud. It is evident that while the points are not distributed at random there is not a clear functional relationship. Consideration of a pair of points such as A and B or C and D, Figure 2, show the difficulty in assessing the hazard of a particular dust cloud.

Similar scatter is evident when using other types of instruments to determine the concentration of a cloud made up of mineral-dust of widely different physical characteristics. Which, if any, of the samplers is giving a correct indication of health hazard? To answer this question more research work, both technically and medically, is required. Meanwhile the 7000-odd measurements of dust concentration collected to date are being analyzed using a multiple regression technique. It is hoped that this analysis will elucidate the effects of particle size distribution, density and shape on the concentration index given by the various sampling instruments.

The research work on comparison of dust sampling instruments is being extended to dust clouds of aggregated particles and possibly to those of spherical particles of known size and density. Many dust clouds in mines contain aggregated particles and these may result in different instrument relationships. It is hoped that the use of spherical particles will enable the collection characteristics of the various samplers to be defined with greater accuracy.

Compositional analysis

Compositional analysis is especially important because of the large range of conditions encountered in Canada where the proportion of free silica, believed to be one of the minerals most hazardous to health, varies widely from one location to another. The dust sample for analysis should contain only the fine respirable fraction of the airborne dust, as it has been shown that this fraction may contain a three times greater proportion of free silica than the total airborne dust (4).

The object of this work is to simplify methods of analysis and their application to mine dusts. Particular emphasis is being placed on development of methods in which samples collected by instruments suitable for routine dust surveys are analysed with a minimum of further handling.

A literature survey of methods of compositional analysis for silica and asbestos is in progress, and some preliminary experiments have been carried out to determine the sensitivity of X-ray diffraction and infra-red absorption techniques. In these experiments small quantities of silica were collected on a filter paper. The filter complete with dust sample was then examined by either X-ray diffraction or infra-red absorption by other Mines Branch personnel in Ottawa. It was possible to measure 0.1 milligram quantities of silica with both techniques. If this approach can be developed successfully, a fairly small gravimetric sampler could be used for collecting the respirable fraction of airborne dust for compositional analysis.

Size distribution of airborne dust clouds

Size distribution analysis of dusts is

Table 1 — Dust sampling instruments

Assessment Measure	Collection Method	Size Selection Method Oversize	Size Selection Method Undersize	Airflow	Manufacturer
Mass	Electrostatic precipitation	none	none	3 cfm	Mines Safety Appliances
Mass	Filtration	none	Filter efficiency	4 cfm (modified)	Staplex
Mass	Filtration	none	Filter efficiency	1 cfm	Open Filter
Mass	Filtration	Horizontal Channel*	Filter efficiency	50 litre/min (1.75 cfm)	Casella (Hexhlett)
Mass	Filtration	Horizontal Channel*	Filter efficiency	2.5 litre/min	Casella (NCB/MRE)
Number by Microscope	Thermal precipitation	Microscope Assessment	Microscope Assessment	7 cc/min	Casella
Number by Microscope	Thermal precipitation and settlement	Horizontal Channel*	Microscope Assessment	2 cc/min	Casella (Long period dust sampler)
Number by Microscope	Impingement onto glass	Microscope Assessment	Collection efficiency	snap sample	Konimeters (Gathercole, Leitz Haslam)
Number by Microscope	Impingement into liquid	Microscope Assessment	Collection efficiency and microscope limitations	0.1 cfm	Mines Safety Appliances (Midget Impinger)
Number by Microscope	Impingement into liquid	Horizontal Channel*	Collection efficiency and microscope limitations	0.1 cfm	Mines Safety Appliances (Modified)
By light scatter degrees	none	Settlement chamber	none	snap sample	Leitz (Tyndalloscope)

*These size selectors have the performance recommended by the Medical Research Council (unpublished) and the Johannesburg conference (3).

Table 2

Dust Type Size	Mass Concentration mg/m3		Number Concentration Particles/cc				
	Total	Respirable	Thermal ½-5μ	Precipitator 1-5μ	Impinger > 5μ	Konimeter > 5μ	Tyndalloscope Degrees
COAL:							
Coarse	2.23	0.94	193	102	90	500	4.20
Fine	1.04	0.85	640	230	136		5.75
SILICA:							
Coarse	2.00	0.74	219	92	88	465	4.50
Fine	2.10	1.67	765	322	157		8.9
PYRITE:							
Coarse	4.33	0.97	221	77	127	475	3.46
Fine	1.70	1.50	2250	200	138		5.45
MICA:							
Coarse	3.61	2.5	575	295	295		6.95
Fine	3.3	2.9	1365	445	460		8.9
ASBESTOS:							
All Particles	1.16	0.77	620	6	115	1600	7.1
Fibrous			500		28	3	

essential in evaluating dust sampling instruments and in relating their size collection characteristics to lung retention curves. Size distribution analysis is also required to evaluate the health hazards of various types of mining operations. Each method of size distribution analysis depends on a particular property of the dust such as projected area, volume, falling speed or surface area; therefore each is likely to give a different size distribution for a given dust. However, these differences give information on aggregation, shape and surface area of the dust particles and so it is desirable to use a number of methods.

The methods at present available in the laboratory are:

1. Visual assessment by projected area of the particles collected on thermal precipitator slides; optical microscope and electron microscope at Mines Branch, Ottawa.
2. Electronic assessment by volume of the particles collected by an electrostatic precipitator after redispersion in an electrolyte: Coulter Counter.
3. Mass assessment by falling speed

of particles redispersed in a liquid: Sedimentograph.

4. Surface area assessment by permeability measurements on a dust bed collected on a filter.

It is hoped to extend this study to include the method of size analysis in which the flashes of light, scattered by individual dust particles passing through a high intensity light beam are sized and counted electronically.

Rock-dust relationships

It is possible that a rock with known properties when subjected to the action of a dust producing mechanism of known characteristics, will produce a dust cloud in the respirable range of predictable properties. The objective, therefore, of this part of the research program is to investigate the relationship between rock properties and dust clouds.

The first task is to review available information on mine rocks and to define those properties which are likely to be relevant such as: physiologically active and inactive minerals; fabric, grain size and distribution; and microstructure. Additional properties may be required to index these rocks which will have to be determined by experimentation. Also during this initial phase, a standard dust producing, collecting and dispersing technique will be developed.

Conclusions

These environmental studies should provide useful information. Industry will be kept informed of progress and practical findings. In addition, for any industrial group conducting research on mine air, the cooperation of the Mines Branch Dust Laboratory is available. □

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Section 6 - Chapter 36

Dust-Sampling Research and Its Application to Mining

by

G. Knight

The Canadian Mining and Metallurgical (CIM) Bulletin

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RECHERCHE DANS L'ÉCHANTILLONNAGE DES POUSSIÈRES ET APPLICATION À L'EXPLOITATION MINIÈRE

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RÉSUMÉ

Les résultats d'un programme de recherche sur les poussières réalisé au Laboratoire de la Direction des mines à Elliot Lake indiquent que la concentration des poussières varie grandement, selon l'instrument d'échantillonnage utilisé, la technique d'évaluation adoptée et les propriétés du nuage de poussières. Comme le rapport entre les estimations de toute paire d'instruments varie beaucoup, la corrélation établie entre le danger pour la santé et les estimations de la concentration des poussières par la plupart des instruments d'échantillonnage actuels doit être mise en doute.

Des études importantes sont réalisées pour définir en termes techniques plus précis les milieux miniers. Il est question dans le présent article de l'influence du classement granulométrique, de la propriété physique mesurée, de la composition et de la période d'échantillonnage sur l'évaluation des dangers pour la santé.

Dust-Sampling Research and Its Application to Mining

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ABSTRACT

Results of a program of dust research carried out at the Mines Branch Laboratory, Elliot Lake, indicate that dust-concentration estimates vary greatly, depending on the sampling instrument, the assessment technique and the properties of the dust cloud. The wide range of the ratio between the estimates by any pair of instruments shows that the correlation between the health hazard and dust-concentration estimates by most existing sampling instruments must be questionable.

Important studies are being carried out to permit the definition of mine environments in more precise technical terms. The influence of size selection, the physical property measured, composition and sampling period on the assessment of the health hazard are discussed.

GEOFFREY KNIGHT was born in Oxfordshire, received his early schooling in private schools in England and graduated from the University of London in 1946. He was a research assistant at the Kodak Research Laboratories from 1943 to 1953, and then joined the Dust Group of the National Coal Board Mining Research Establishment in Middlesex as a research scientist. He emigrated to Canada in 1965 and joined the Department of Energy, Mines and Resources, Mines Branch, Elliot Lake. His present position is research scientist in charge of the Dust Research Laboratory at the Mining Research Centre, Elliot Lake Laboratory.

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INTRODUCTION

DUST INHALED AND DEPOSITED in the lungs of miners creates a potential health hazard. Dust measurements are required to indicate this health hazard and the need, if any, for dust control. Dust measurements include the determination of physical and chemical parameters of the dust cloud and, clearly, the parameters measured should be related to those that define the biologic effects.

This report discusses basic considerations, research and recent advances in dust sampling as applied to routine mine dust surveys and to special research studies.

BASIC CONSIDERATIONS

As the main hazard is pneumoconiosis in its many forms, silicosis, anthracosis, etc., dust sampling should be directed toward estimating the potential pneumoconiosis hazard of airborne dust. To do this, it is essential to consider the physiological processes involved in pneumoconiosis and to measure dust in terms of the appropriate parameters. There are a number of factors relating the dust cloud to the onset of pneumoconiosis:

1. deposition of dust in the lungs;
2. clearance of dust from the lungs;
3. biologic activity of dust in the lungs.

Deposition of Dust in the Lungs

The only dust that can be deposited in the alveolar region of the lung is that remaining in the inhaled air after passing through the respiratory tract (mucous-swept airways). Three physical mechanisms — impaction, gravity settlement and diffusion — are instrumental in the deposition of dust in both the respiratory tract and the alveolar region. One appropriate parameter for describing the behaviour of a particle in these three mechanisms is its 'aerodynamic size.' The aerodynamic size is defined as the diameter of a unit-density sphere having the same settling velocity or mobility as the particle in question.

The general dependence of alveolar and respiratory-tract deposition on size and breathing rate is shown in *Figure 1;* however, the precise values vary with the breathing pattern and with the individual(1). There is, in general, a minimum deposition for particles about 0.5 μm in size. Impaction and gravity-settlement deposition increase with increasing particle size and are responsible for most of the deposition at sizes above the minimum. Diffusion deposition increases with decreasing size and is the main mechanism below the 0.5-μm size.

In order to define the alveolar-deposition potential of an airborne dust cloud, the size distribution should be specified in terms of the aerodynamic size. Other measures of particle size may give misleading results; for example, coal particles with an aerodynamic size of 5 μm may have projected areas equivalent to that of 5- to 15-μm-diameter circles⁽²⁾.

Clearance of Dust from the Alveolar Region of the Lungs

The mechanisms of clearance are not as clearly understood as are those of deposition. Experimental studies, reviewed by Hatch and Gross⁽¹⁾, have suggested that clearance is dependent on the composition, size distribution, shape and concentration of the deposited dust.

Experimental studies⁽¹⁾ have suggested that the clearance mechanism has a half-life of 20 days or more, and only at extremely high dust concentrations has there been a suggestion of a breakdown in this mechanism. This slow rate of clearance suggests that the average dust exposure over a period of at least 20 days would be important rather than peak exposures, unless they are extremely high, but the most relevant parameters for expressing these factors are not known.

Biologic Effect of Dust in the Lungs

The physical and chemical factors determining the biologic effects are: concentration, size distribution, composition, shape and residence time. Again the relevant parameters in terms of which these factors should be expressed are not known. There is considerable support for the view⁽³⁾ that the mass of coal dust is the appropriate concentration parameter in coal miners' pneumoconiosis and that the surface area of silica dust is applicable to silicosis. For other materials and for mixed dusts, no recommendations have been made as yet. Thus, in research applications, fairly comprehensive specifications of the dust clouds need to be made. Because of the uncertainty in both clearance and biologic effects, as much information as possible should be obtained when defining dust clouds for research.

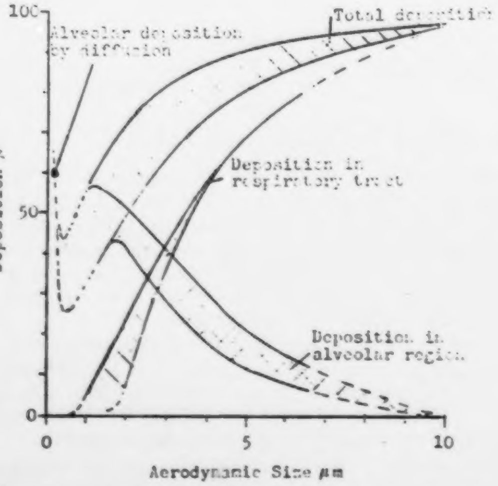

Figure 1.—Dust deposition in the lungs, showing range of variation with the breathing rate (after Hatch and Gross⁽¹⁾).

DUST RESEARCH

The first five parts of this section relate to routine mine sampling and the final part to detailed research studies.

Comparison of Dust-Sampling Instruments

A number of studies have been carried out comparing routine dust-sampling instruments in mine air and in laboratory dust chambers. One of the most comprehensive of these was carried out in the Mines Branch dust chamber at Elliot Lake⁽⁴, ⁵⁾. In this study a wide range of routine and experimental dust samplers were compared in twenty-two types of dust cloud prepared from six materials by five methods of dispersion to give dust clouds with a wide range of concentration, size distribution, state of aggregation, particle density and particle shape.

The dust-sampling instruments included in this study determined dust concentration in terms of the parameters mass, number and light scatter. The light scatter parameter is dependent on the surface

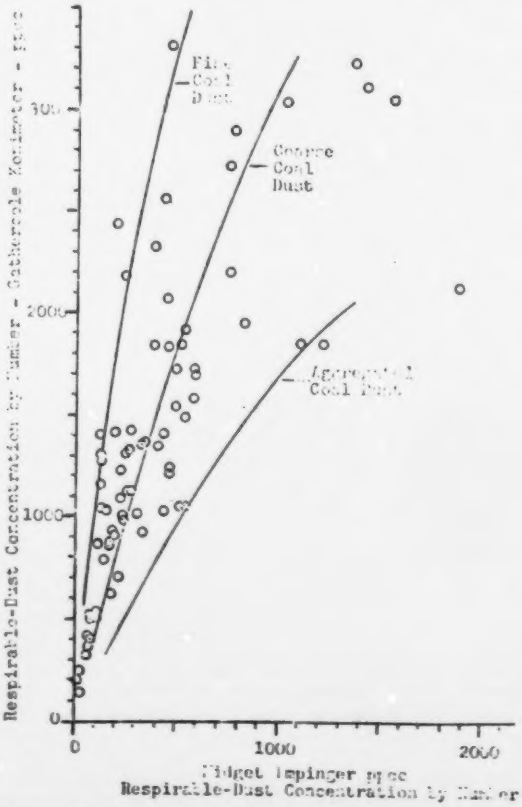

Figure 2.—Comparison between instruments assessing dust BY NUMBER with "best-fit" lines by statistical regression.

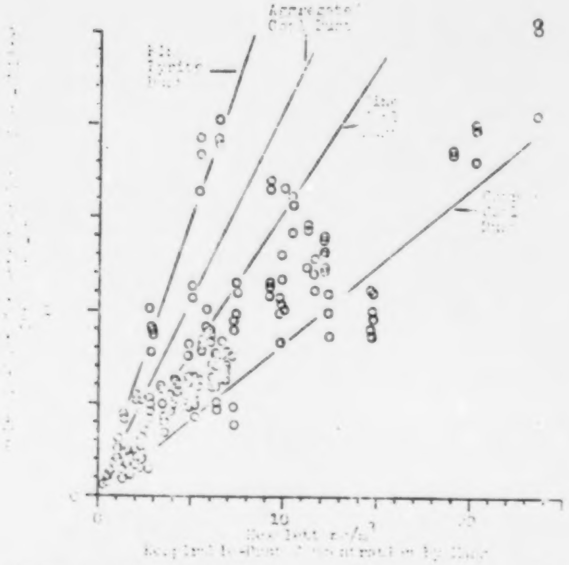

Figure 3. — Comparison between instruments assessing dust BY NUMBER AND BY MASS with "best-fit" lines by statistical regression.

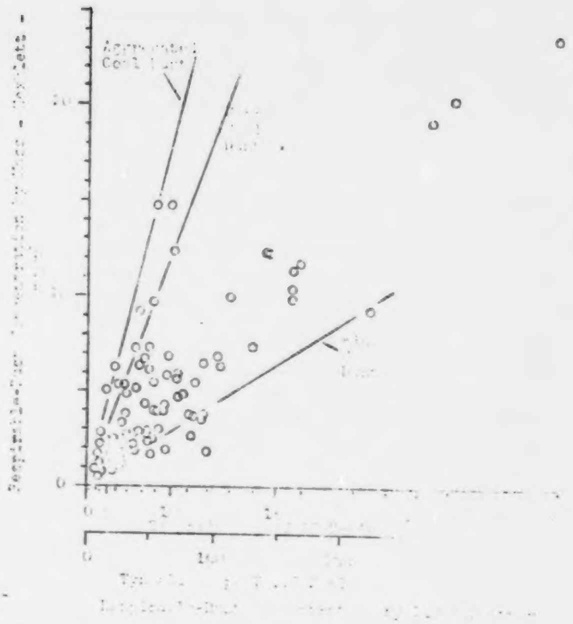

Figure 4. — Comparison between instruments assessing dust BY MASS AND BY LIGHT SCATTER with "best-fit" lines by statistical regression.

area of the dust particles, but not in a simple manner, as the optical properties of the materials forming the particles can have a large effect.

These dust-sampling instruments were:

By Mass — an electrostatic precipitator, with three open filters to measure total airborne dust, and seven filters preceded by horizontal elutriator(6,7) or cyclone(8) size-selectors intended to simulate the behaviour of the respiratory tract in removing coarse particles from the inhaled air. The dust was assessed by weighing on a sensitive balance and the concentration was expressed in milligrams per cubic metre (mg/m^3).

By Number — three types of sampler — thermal precipitators, midget impingers and konimeters. The number concentrations were assessed by visual counting, using an optical microscope, and expressed as particles per cubic centimetre (ppcc). High-resolution microscopy was used on the thermal-precipitator samples and the count obtained in a number of size ranges. The impingers and konimeters were assessed by the techniques recommended by the United States Bureau of Mines(9) and the Mines Accident Prevention Association of Ontario(10), respectively. Konimeter samples were counted both before and after the recommended heat and acid-wash treatment.

By Light Scatter — one instrument, the Tyndalloscope (Leitz, Germany, Model T II). The scattered light is proportional to the square of the angle between the polarizing screens in the balancing beam. The units are given as $\sin^2\theta$, where θ is the angle indicated on the dial. Another later version of the Tyndalloscope (T III) is graduated with units proportional to $\sin^2\theta$.

Some 8,000 measurements of dust concentration were obtained in the main comparison of dust-sampling instruments. Most of these were analysed using a statistical regression analysis and a computer. The most important results of this study are presented briefly here.

A comparison between a pair of dust samplers, the impinger and the Gathercole konimeter (without heat treatment and acid wash), assessing dust by number in dust clouds prepared from coal, silica, pyrite and mica, is shown in *Figure 2*. A wide scatter in the ratio of dust concentrations measured by these two samplers is evident. For instance, an estimate of 1000 ppcc by the konimeter could correspond to an estimate of 100 to 550 ppcc by the impinger. Also shown in *Figure 2* are some curves obtained by statistical regression analysis for the relationship in individual types of dust cloud. The standard deviation is about 70 per cent for a single observation of the ratio between the two instruments in one type of cloud. A comparison between instruments assessing respirable dust by number and by mass is shown in *Figure 3*, and a comparison between those assessing respirable dust by mass and by light scatter is shown in *Figure 4*. As can be seen, a similar variability and scatter of results was obtained. This variation was also found in all the other comparisons between instrument types.

The large variations between different types of dust sampler can be attributed to a number of factors; size distribution and aggregation are the main ones. One typical effect of size distribution is shown in *Figure 5*, where the comparison index between two samplers is shown plotted against a size classification. The effect of aggregation is particularly marked in comparisons with the impinger, because the aggregates are dispersed and the particles counted individually with this instrument. For instance, in both *Figures 2* and *3* the impinger shows a greater relative concentration in the aggregated dust clouds than in the other coal-dust clouds. One point to note in these comparisons is that the relationships between the measurements by all the instruments except the konimeters are linear with respect to concentration. The non-linearity of a konimeter was shown by the 'best-fit' lines in *Figure 2*.

When dust clouds containing fibrous particles prepared from asbestos or glass fibre were examined, the variations between the instruments were even wider. The main sources of this scatter of results were in instrument collection and in microscope resolution of the fine fibres.

Size Selectors for Routine Dust Sampling

A number of size selectors have been proposed for routine determinations of respirable dust based on the collection of coarse non-respirable dust particles by horizontal elutriators(6,7,11) or cyclones(8,12). The United Kingdom Medical Research Council(3,4) and the United States Atomic Energy Commission(5) have both made recommendations for size-selective samplers based on experimental studies(1) of lung deposition. A comparison(13) of size selectors in the Mines Branch dust chamber in a wide range of dust clouds showed the practical equivalence of these recommendations.

The South African gold mines are supporting the development and application of a non-aerodynamic size-selective method DISA(14). This is based on an optical-diffraction size analysis, by projected area, of the particles collected by a thermal precipitator.

New Sampling Instruments Based on Measurements of Concentration by Mass or Surface Area

The measured physical parameters chosen to characterize the dust cloud should be related to those determining the biologic effects. The *mass* of coal dust in the lung is considered to be the best single measure of its health hazard(2), whereas the *surface area* of silica dust is considered as most closely related to the health hazard(3). No specific recommendations based on biologic effects have been made for other dusts or for mixed dusts.

A number of size-selective gravimetric samplers have been developed. These fall into three classes: (1) high-sampling-rate instruments with external power sources, such as the Hexhlett(15) and the Batt(16); (2) small portable self-contained instruments such as the NCB MRE gravimetric sampler(17); and (3) small personal samplers using cyclone size-selectors(18,19) for sampling the breathing zone of one man rather than a fixed position in the working place.

No direct methods for measuring surface area are suitable for routine dust sampling. However, two techniques are being developed, based on optical methods for measuring the projected area of the dust particles. One, a laser technique(20), measures the projected area of dust suspended in air, and might be developed into an instrument capable of taking direct dust readings underground. The second, an optical diffraction technique — the South African DISA(14) — measures the projected area of dust particles collected on a thermal-precipitator slide.

Compositional Analysis

The composition of the dust cloud can have a very great effect on its health hazard. Although both coal and silica dust can lead to diseases of the lung, one part of silica produces approximately the same debilitation as fifty parts of coal when deposited in the lung. The knowledge of the health hazard of other dusts and of mixed dusts is limited, but it is generally agreed that in their hazard most are intermediate between silica and coal. Asbestos may be even more hazardous than silica. For mixed dust containing silica, various assumptions can be made relating its toxicity to its silica content(21); the threshold limit values recommended by the A.C.G.I.H.(22) are shown in *Figure 6*.

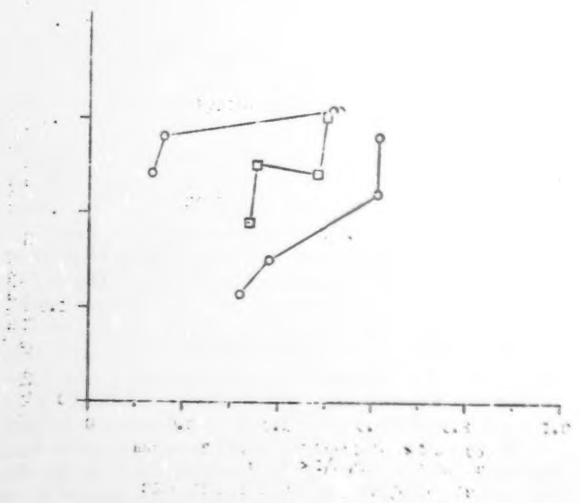

Figure 5. — Effect of size and density on the comparison between the impinger and the konimeter.

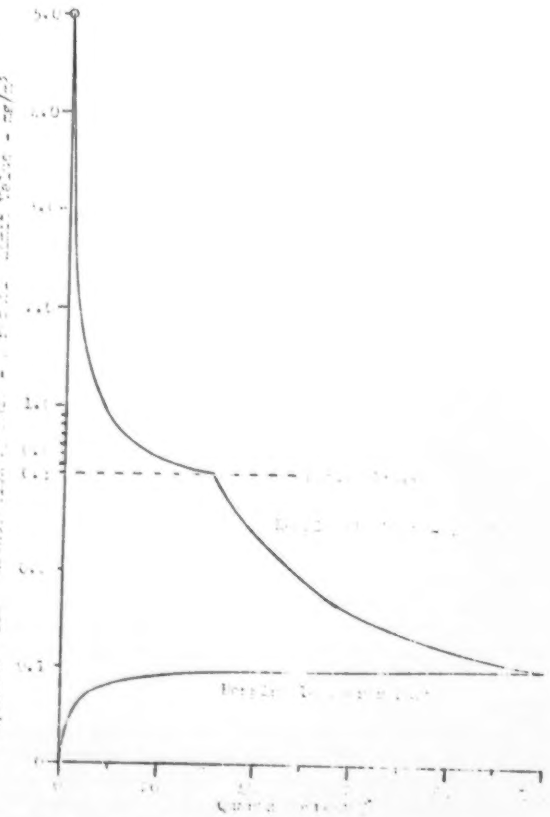

Figure 6. — Threshold limit values for mixed dusts recommended by the A.C.G.I.H.(22).

There are a number of analytical methods capable of determining quartz (silica) in the presence of other minerals, especially silicates. The most suitable techniques would seem to be:

chemical — phosphoric-acid digestion(23)
physical — X-ray diffraction(24)
physical — infra-red absorption(25)

These three techniques produce results which can readily be expressed in terms of mass, but not in terms of surface area. Most mines working highly siliceous rocks have airborne dust clouds containing less than 50 per cent silica by mass in the respirable size-range and, in the presence of minerals — such as mica — with a relatively high surface area, it is difficult to obtain a reasonable estimate of silica in terms of surface area.

Canadian operators mine a wide range of minerals, producing dust clouds with high to low silica contents, as well as coal and even some asbestos. In this wide range of conditions, compositional analysis on a routine basis is often desirable. *Figure 6* shows the large changes — 0.19 to 5 mg/m^3 — in total dust level permitted over the range of quartz content. However, this figure also shows that the permitted quantity of quartz is effectively constant — 0.09 to 0.1 mg/m^3 — in the 10 to 100 per cent quartz content range and that the concentration of quartz alone could be used as a single parameter in the high-silica mines rather than using the two parameters (concentration of total dust and the fractional quartz content).

Sampling Period

The advent of mechanization in mines has sometimes resulted in large variations in dust concentration during a shift. This has led to discussion of the merits of the measurement of peak concentration as an assessment of the health hazard. It has been concluded(3,26) that the average concentration over a long period, such as a shift, is the best estimate. However, if excessive peaks occur they should be recorded separately(3). The United Kingdom coal mines have adopted long-period (shift) samplers in routine sampling(27).

Allied to shift sampling has been the suggestion that easier control of pneumoconiosis might be obtained by limiting the miners' total-dust exposure rather than by limiting all mining operations to a maximum dust level as is applied in Germany(28).

There has been research into the variability of dust levels with time, and statistical controls of sampling frequency have been suggested(29,30).

Advanced Techniques for Research Studies

In studies of dust clouds, in which the main object is elucidating relationships with medical effects or determining the health hazards of mining processes, more detailed knowledge of the physical and chemical properties may be required. The method of determining these properties should relate to the parameters which apply in the lungs. In composition studies, for instance, large differences have been found between the silica content in the respirable portion and in the total airborne dust.

Size-distribution studies can be divided into three regions:

1. Airborne dust — as it affects lung deposition in the greater than ½-μm size range.
2. Airborne dust — as it affects lung deposition in the less than ½-μm size range.
3. Respirable dust (i.e. that part of the total that can be deposited in the alveolar region) — as it affects clearance and the onset of pneumoconiosis.

In size-distribution studies, two properties — quantity and size — appear. These can be expressed in terms of many parameters. For quantity, the parameters number, surface area, mass, etc. have been used. For size, those used have been projected area, settling velocity in liquid, aerodynamic size, volume, etc. The ones appropriate to the biologic effect should, if possible, be chosen.

A simple field technique, based on aerodynamic size, has been proposed in the Elliot Lake Dust Laboratory for use in region 1 above and is, at present, being checked against other methods. The only techniques based on aerodynamic size applicable in region 2 are difficult to apply in the field and are time-consuming.

For region 3, studies should be applied to dust after collection by an aerodynamic size-selective technique to minimize the effects of breakup of aggregates large enough to be deposited in the respiratory tract.

The bulk of the mass of the surface area is accounted for by the dust in region 1, and the techniques available in the Mines Branch Laboratory — optical and electron microscopy of thermal-precipitator slides, and Coulter Counter measurements — can probably give an adequate picture of the dust cloud. Research in size-analysis techniques is aimed at the improvement of automatic equipment to decrease the time spent in analysis. However, a limited amount of microscopy will always be desirable to determine the shape of particles.

In research studies, a detailed specification of the dust composition is required and laboratory techniques for the compositional analysis of minerals in small samples are being developed. It is hoped to apply these techniques to the variations in composition of the dust in various size ranges and from various breakage processes, both in the laboratory and in the field.

CONCLUDING REMARKS

Excellent progress in establishing the relationship between dust and health in coal mines is being made by a combined technical-medical study in the United Kingdom(31). Considerable progress(27,32) is also being made in high-silica gold mines by similar studies in South Africa(33).

The relationships for the mixed dusts found in most other mines are possibly more complex and, although many excellent studies have been carried out on limited aspects of the problem, there would seem to be a need for a combined technical-medical study in the mining industry to elucidate many of the problems and allow a more knowledgeable estimate of permitted dust levels to be made.

The first requirement in this is to set up a dust-sampling system that will give good estimates of the total dust to which the miners' lungs are exposed.

Mines Branch dust research is directed toward the detailed study of dust measurement, including size distribution, shape and composition, both in laboratory studies of rock breakage and in mines.

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Section 6 - Chapter 37

Airborne Contaminants and Ventilation in Mines

by

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CONTAMINANTS ATMOSPHÉRIQUES ET VENTILATION DANS LES MINES

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Les principales sources de contamination de l'air dans les mines sont : 1) la poussière minérale - fracturations récentes; redispersion; 2) les vapeurs d'huile - équipement fonctionnant à l'air comprimé; 3) les gaz d'échappement des moteurs diesels - particules solides (surtout de carbone), oxyde d'azote, monoxyde de carbone, hydrocarbures irritants; 4) fumées d'explosifs; 5) émissions de gaz - méthane, radon, etc.

Ces problèmes, causés par des contaminants et par une chaleur excessive, ainsi que les besoins en ventilation nécessaires à leur élimination sont traités dans le présent article. Les trois principales méthodes de ventilation et d'élimination des contaminants (dilution, expulsion et approvisionnement individuel d'air pur aux mineurs) sont décrites.

Airborne Contaminants and Ventilation in Mines

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The major sources of contamination in mine air are: (1) Mineral dust — fresh breakage; redispersion. (2) Oil mists — compressed-air-operated equipment. (3) Exhaust emissions from diesel engines — particulates (mostly carbon); nitrogen oxides; carbon monoxide; irritant hydrocarbons. (4) Blasting fumes. (5) Gas emissions — methane, radon, etc.

These problems, caused by contaminants and by excess heat, are discussed in this paper, together with the ventilation requirements for their control. The three main modes of ventilation and contamination control — dilution, exhaust, and clean air supply to individual miners — are described.

Introduction

Levels of airborne contaminants are becoming a more stringent limiting factor in mining and the need for every mining engineer and miner to understand their control is becoming more necessary. As mines deepen, control becomes more difficult and a further factor, heat, will have to be considered.

Contaminants and Their Sources

The major contaminants, their characteristics and their sources are described in this section.

MINERAL DUST

In mines, mineral dust is almost all formed by breakage of rock. Dust may be dispersed into the air either directly from fresh breakage or by disturbance of previously broken rock.

The amount of potentially airborne (fine) dust produced is dependent on the amount of breakage. The coarser of the material produced the smaller the proportion of fine dust; i.e., a sharp drill bit cuts faster, producing larger chips and less fine dust. In falls of rock, the amount of airborne dust produced from fresh breakage is roughly proportional to the energy input or the distance dropped.

Water sprays usually do not remove fine dust from the air, but act by wetting the fine dust and binding it to the coarse before disturbance can disperse the dust into the air. Water can be very effective in reducing dispersion of already broken dust into the air, but it is ineffective in controlling dust from fresh breakage unless applied to the breaking point, as in wet drilling.

Table 1 shows some preliminary measurements that have been made of dust production in mining operations, together with the volumes of clean air required to dilute the dust to permitted levels. These measurements were made in a small number of mines and the results were very variable, ranging from half to twice the quantities given in the table, and depend on many factors, such as water sprays, material size, etc.

The results shown in Table 1 can be used for the prediction of air requirements. Taking the example of a scooptram (ST8) hauling 600 tons in an operating period of 400 minutes from a drawpoint to an orepass, the air flow required to control dust in a low-quartz ore is calculated as 15,000 cfm.

This airflow is close to that required to control the concentration of contaminants from the diesel engine exhaust gases at the usual 75 cfm per brake horsepower, i.e. 17,000 cfm. However, for high-quartz mines the airflow required is much greater (about 65,000 cfm).

The table shows that the major dust sources are blasting and material handling and emphasizes the need to carry out main blasting between shifts. Clearly, the fixed rock-handling installations, ore passes, crushers and probably skip loaders produce very large quantities of dust and careful control is essential to avoid passage of this dust to working places.

This paper was presented during Session No. 1 at the 2nd Annual Underground Operators Conference, sponsored by the Metal Mining Division of CIM, in Val d'Or, Quebec. Session Chairman was J.E. Belford, Mine Superintendent, Underground, Texasgulf Canada Ltd.

TABLE 1 — Dust Production and Air Volume for Dilution

Dust Source	Dust Production (1)	Dilution Air(2)	
		<10% Qtz.	50% Qtz.
	mg per ft drilled	ft^3 per foot drilled	
Jumbo Drill(3)	60	2100	2100
Jackleg(3)	35	1200	1200
	mg per ton	ft^3 per ton	
Blasting(4)	2000	35000	300000
Mucking(5)	100	3000	4000
Scraping	50	2000	15000
Load-Haul-Dump(6)			
— Development	1000	30000	30000
— Tramming	600	10000	45000
Chute Loading(7)	40	700	7000
Ore Passes	700	12000	120000
Crushing	700	12000	120000

(1) Dust production expressed as milligrams of dust produced for each foot of hole drilled or ton of ore handled or broken.

(2) Dilution air required to control dust to target values for mines with low and high quartz contents in the ore.

(3) Oil mist is the main contaminant in drilling with compressed-air-operated drills and is the controling factor in the amount of dilution air required.

(4) An estimate based on dust reaching the surface after a main blast.

(5) Compressed-air mucker on rails.

(6) For diesel-powered equipment; includes dilution required for carbon particles in the exhaust.

It is apparent that there are a number of problems relating to ore passes caused by air-pumping of falling material.

(a) Angle of ore pass to vertical; i.e. tendency of rock to fall freely in a vertical pass rather than slide, as in an inclined pass.

(b) Rate of feed of rock relative to size of ore pass. Ore is usually passed one carload at a time as dumped. If this quantity is sufficient to fill a few feet of the ore pass it can act as a piston pushing the air ahead. A slow controlled feed might greatly decrease the pumping action.

(c) The existence of interconnections between parallel waste and ore passes. This allows pumped air to recirculate rather than blow out through the lower-level dump points.

(d) Adequate control of the emptying of the ore pass. This prevents dusty air from being pushed straight out of the bottom.

(e) Relationship between size of openings, leakage through doors and volume of air extracted.

The control of dust at crushers and skip loaders should be by standard enclosure and extraction systems, with or without a filter. In underground crushers, relatively small quantities of air are required to contain dust produced in the crusher. This quantity may not be adequate to clear blasting fumes from secondary blasting in a reasonable period and provision should be made for this.

Ore handling in stopes and drawpoints produces considerable quantities of dust; thus, the workings and the ventilation should be set up to carry this dust away from other miners. Work in places downwind of rock-handling operations should be scheduled so as to avoid high-dust periods.

An important facet of mineral dust is its quartz content. The quartz content of the airborne material tends to be less than that of the rock because the quartz is stronger and less readily broken than most other minerals. It should be noted, however, that the figure expressing the percentage of quartz in the total airborne dust may be less than that expressing its percentage in the mineral component because of the presence of non-mineral dusts.

OIL MISTS

Compressed-air-operated equipment uses lubricating oil, some of which is sprayed out as fine droplets which can penetrate to the alveolar region of the lungs and possibly form a health hazard.

Some preliminary results have showed that about 0.3% of the lubricating oil in drills is atomized into respirable sizes and that this forms 90% of the weight of the material collected on a filter by a respirable-dust sampler, the other 10% being mineral dust. Thus, in most drilling sites, ventilation is needed to reduce oil mist levels rather than mineral dust.

DIESEL-POWERED EQUIPMENT

The exhaust of diesel engines contains four major noxious components — particulates (mainly carbon), nitrogen oxides, carbon monoxide and irritant hydrocarbons. In some cases, the amount of heat is also troublesome. In the past, the immediate hazard to health, the gases, have been recognized and the long-term hazard, particulates, ignored. Although there is no published threshold limit that is applicable to diesel-exhaust particulates, it is clearly undesirable to continue to ignore the possible ill effects. The highest concentration of diesel particulates detected in a mine was 10 mg/m^3; the usual level is 0.5 to 3 mg/m^3, and it is suggested that levels should be controlled to 1 mg/m^3 (1). The dilution levels suggested in Table 1 include an allowance for exhaust particulates.

BLASTING

Blasting produces large quantities of mineral dust, non-mineral dust, nitrogen oxides and some other contaminants. Thus, most blasting is now carried out between shifts and there is time for the dust and fumes to be cleared from the working places prior to re-entry.

Secondary blasting in development ends, ore passes, crusher rooms, etc., however, does take place during the shift and it is very desirable that ventilation should be adequate to clear the fumes and dust quickly prior to re-entry. Exhaust ventilation properly placed may be more effective than blowing in permitting rapid re-entry.

GASEOUS EMISSIONS

Some mines are troubled by noxious gases issuing from the rock; methane and radon are the major problems, but others occur and need to be recognized. Ventilation is essential to dilute these gases to safe levels, with adequate velocities, a minimum of 50 ft/min., to ensure mixing.

It should be noted that the emission of radon gas with the attendant radiation hazard is not restricted to uranium mines; Newfoundland Fluorspar is a well known example and significant quantities of radon gas have been found in other mines.

Any unventilated section of a mine may have hazardous concentrations of contaminants or a lack of oxygen, and should not be entered.

HEAT

Men can work comfortably only in a limited range of air conditions. As mines deepen, rock temperatures and air temperatures tend to rise. It is necessary to ensure that the air supplied to working places has enough heat capacity to keep temperatures to acceptable levels. Air cooling may be necessary, in which case the surplus heat is passed to the chilled water supplied.

Ventilation

Three main methods of air ventilation can be used to control the exposure of miners to airborne contaminants:

(1) dilution ventilation, i.e. enough air everywhere to dilute contaminants to safe levels;

(2) exhaust ventilation, to entrain the contaminants and carry them away from the workers;

(3) clean air supply to the individual miners, by means of (a) respirators using lung-powered filtration, (b) respirators using mechanically powered filtration, (c) air-supplied respirators, (d) air-supplied hoods or (e) air-supplied booths.

In mining, a combination of all three methods is used. Dilution ventilation alone requires very high volumes. Exhaust ventilation can require much less air, as little as one tenth, and individual air supply much less again. Speaking generally, one can say that the extractive areas of mines are usually ventilated by dilution and the crushing and ore passes by extraction. At some control jobs, such as at skip loading, ventilation is provided by clean air supply to a booth. Some mines have equipped LHD units with air cylinders and air-supply respirators.

Although air quality can be improved by increasing the volume of fresh air supplied, it would seem that exposure could, in many cases, be more readily reduced by modifications to layout and ventilation to enable the air from the major material-handling operations to be routed directly to the exhaust. Work in the return airway from such sites should be scheduled in non-productive periods.

Filtration and recirculation of air is suitable when the hazard is not due to gases. Radon is possibly the only exception to this, because the hazard is mainly from the solid radioactive decay products, which can be removed by filtration and take time, possibly 10 minutes, to build up again in the filtered air. If the air is reused after filtration, as for instance in a crusher room, a high-performance filter is essential and maintenance must be very good to maintain its performance, because in many installations over a period of time more dust leaks through holes than through the cloth. Gases can be removed by suitable chemicals or by activated charcoal, but these systems require relatively frequent maintenance.

The considerations for application of a clean air supply to individual miners are as follows.

(1) Lung-powered respirators may have very efficient filters, but, because of face-piece leakage, can only be relied on to reduce dust exposure by a factor of at the best 10, but often as low as 2. Because of discomfort, the wearing of a respirator is usually only acceptable for short periods and then only when the hazard is obvious to some of the senses or when coarse dust is a nuisance.

(2) Mechanically powered respirators have a much higher protective factor than lung-powered respirators, but are limited by portability and weight considerations. Probably the most suitable application is for light work, such as leaching in mined-out areas, or for use on vehicles.

(3) Air-supplied respirators protect against both dust and gases and have been used on diesel-powered LHD equipment with high-pressure air cylinders.

(4) Air-supplied hoods are very suitable where a few men spend most of the shift in a limited area of a dusty operation, such as a picking belt. Their use many permit the general dust levels during operation to be 2 or 3 times higher than the target value for exposure. If only dust is the problem, then a filtered air supply may be adequate; however, if gases are also present, a fresh-air source should be brought in.

(5) Air-supplied booths are most suitable where the operator spends most of his time sitting and operating controls. The remarks made in (4) above apply equally here.

Reference

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G. Knight was born in Thame, Oxfordshire, England, and graduated from the University of London in 1946 with a general B.Sc He worked at the Kodak Research Laboratory during graduation and joined the dust group of the National Coal Board's Mining Research Establishment in 1953. He emigrated to Canada and joined the Federal Government's Mining Research Centre as a dust research scientist in 1965.

APPENDIX A

Listing of Internal reports: Titles Only

This appendix lists most internal reports produced by CANMET laboratories on dust-in-mines related topics excluding most reports on the two topics: Dust in diesel engine exhaust gases and Dust in coal mines where they were carried out by the Canadian Explosive Atmospheres Laboratory and the Coal Research Laboratory respectively.

The titles, authors and reference numbers of the papers are given. The reports are sorted by subject and presented chronologically within each category. The 5 main categories used in the main text are used together with further subdivision when required. The categories used are listed below:

1. Dust sampling and assessment
    a. Experimental techniques
    b. Comparisons of dust sampling techniques
    c. Dust sampling methods for routine use in mines
        i. Air sampling aspects
        ii. Assessment techniques
        iii. Sampling programs and statistics
    d. Continuous monitoring
    e. Sampling and assessment of asbestos and other airborne fibres
2. Mine studies
    a. Dust level surveys
    b. Dust generation and production studies
    c. Dust control studies
3. Dust characterization– composition and size distribution
4. Dust standards and assessment principles
5. General

A total of about 200 internal reports are included in this listing. Some reports are listed in more than one category.

Listing of Internal Reports: Category 1. a.
Dust Measurement Instrumentation: Experimental techniques

1. Richards, L. "Construction details of the dust chamber and dust feed mechanism"; FMP-63/167-MIN; November 1963.
2. Richards, L. "Maintenance and repair of midget impinger pump, tests of vacuum gauge on pump and calibration of impinger nozzles"; FMP- 63/168-MIN; November 1963.
3. Knight, G., and Stefanich, W. "Laboratory dust chamber - II: Dust cloud preparation"; MR-67/41-ID; August 1967
4. Stefanich, W., and Tervo, R.C. "The development and application of an atomizer for the production of dust clouds with aggregated particles"; MR-67/72-ID; November 1967.
5. Knight, G., and Stefanich, W. "Laboratory dust chamber - III: Installation and operation of dust sampling instruments"; MR-68/22-ID; December 1967.
6. Knight, G. "Laboratory dust chamber - IV: The particle size and shape characteristics of the standard dust clouds"; MR-68/34-ID; March 1968.
7. Knight, G. "Comparison of Elliot Lake Laboratory air flow meters"; Mineral Research Program; Mining Research Laboratories; Division Report MRP/ MRL 85-111 (INT).

Listing of Internal Reports: Category 1. b.
Dust Measurement Instrumentation:
Comparisons of Dust Measuring Techniques

1. Cochrane, T.S., and Richards, L. "A laboratory comparison of the tyndalloscope, midget impinger and electrostatic methods of evaluating airborne dust concentrations"; FMP-65/118-MRL; August 1965
2. Knight, G. "Comparison of dust sampling instruments - I: Interim report on pure silica dust"; FMP-66/70-MRL; April 1966.
3. Knight, G. "A laboratory comparison of dust sampling instruments on ore, concentrate and flux from a Quebec smelter operation"; FMP-66/134 -MRL; July 1966.
4. Knight, G. "Comparison of dust sampling instruments - II: Interim report on pyrite dust"; FMP-66/144-MRL; August 1966.
5. Knight, G. "Comparison of dust sampling instruments - III: Interim report on coal dust"; FMP-66/147-MRL; August 1966.
6. Knight, G., Rajhans, G.S., and Stefanich, W. "Comparison of dust sampling instruments - IV: Interim report on mica dust"; FMP-67/6-MRL; December 1966.
7. Knight, G., Rajhans, G.S., and Stefanich, W. "Comparison of dust sampling instruments - V: Interim report on asbestos and glass fibre dust"; MR-67/40-ID; May 1967.
8. Knight, G., Rajhans, G.S., and Stefanich, W. "Comparison of dust sampling instruments - VI: Interim report on coal, silica, pyrite and mica dust clouds dispersed in a jet mill and repeat experiments"; MR-67/71-ID; November 1967.
9. Stefanich, W. "Comparison of dust sampling instruments - IX: Comparison of microscope counting techniques"; MR-67/73-ID; November 1967.
10. Knight, G. "Comparison of dust sampling instruments - X; Analysis of results on non-aggregated dust"; MR-68/11-ID; January 1968.
11. Knight, G., and Stefanich, W. "Comparison of dust sampling instruments - XI: Report on dust clouds of aggregated particles"; MR-68 /33-ID; March 1968.
12. Lichti, K. "Comparison of dust sampling instruments - XII: Collection efficiency with spheres"; MR-68/53-ID; April 1968.
13. Knight, G. "Comparison of dust sampling instruments - VIII: Interim report on statistical analysis technique"; MR-68/110-ID; April 1969.

14. Gray W.M. "The problem of fitting the functional relation $v = \beta u$ when the measurements of both variables are subject to errors depending on the magnitudes of the variables"; MR-69/1-ID January 1969

15. Knight, G. "Comparison of dust sampling instruments - XVI: Recalibration of the McIntyre Research Foundation aluminum-dust sampler"; MR-69/3-ID; December 1968.

16. Knight, G., and Lichti, K. "Comparison of cyclone and horizontal elutriator size selectors"; MR-69/13-ID; March 1969.

17. Gray, W.M. "Discussion of Internal Report MR-68/110-ID"; MR-69 /6-ID; January 1969.

18. Knight G. "Comparison of dust sampling instruments - XIII: Analysis of those assessing dust by number"; MR-69/49-ID; April 1969

19. Knight, G. "Comparison of dust sampling instruments - XIV: Relationships between respirable mass, mean number and light scatter"; MR-69/51-ID; June 1969.

20. Knight, G., and Kowalchuk, R. "Calibration of the modified McIntyre Research Foundation filter paper sampler, a smoke meter and two gravimetric samplers for aluminum prophylactic dust"; MR-70/114-ID; November 1970.

21. Cochrane, T.S., Knight, G., Richards, L.C., and Stefanich, W. "Comparison of dust sampling instruments"; CANMET Research Report R250; October 1971.

22. Knight, G. "Respirable dust samplers: Tentative specifications and test methods"; Internal Report 73-23; February 1973.

23. Knight, G., and Kowalchuk, R. "A comparison of gravimetric dust samplers underground"; MRP/MRL 77-40(TR); March 1977.

24. Knight, G. "A comparison between two mine dust sampling systems"; MRP/MRL 79-87(TR); September 1979.

25. Grenier, M.G., Hardcastle, S., Frattini, A., Butler, K.C. "Comparison of dust sampling instruments in coal and uranium ore dust clouds in a dust chamber"; M& ET/MRL 86-104(TR); 1986.

26. Grenier, M.G., Butler, K.C. "Comparison of respirable dust samplers in an underground uranium mine." M& ET/MRL 86-156; 1986

Listing of Internal Reports: Category 1. c. i
Dust Measurement Instrumentation:
Dust Sampling Methods for Routine Use in Mines:
Air Sampling Aspects

1. Ireland, G. "Calibration of X-ray diffraction equipment with Casella personal samplers: A dust measuring system"; MR-70/121-ID; December 1970.
2. Knight, G., and Kowalchuk, R. "Testing of respirable dust sampling techniques for use in Ontario mines: Part I - Description of techniques"; MR-71/16-ID; January 1971.
3. Kowalchuk, R. "Testing of respirable dust sampling techniques for use in Ontario mines: Part II - Elliot Lake detailed dust measurements"; MR-71/44-ID; February 1971.
4. Knight, G. "Determination of respirable quartz in mine air using personal samplers and X-ray diffraction"; MR-71/78-ID; July 1971.
5. Ireland, G. "Interference of Hydrogen Sulphide Gas with Dust Collection using Silver Membrane Filters"; Internal Report 72/54; May 1972.
6. Knight, G., and Kowalchuk, R. "Testing of respirable dust sampling techniques for use in Ontario mines: Part VII - Instrument mechanical performance"; Internal Report 72-99; August 1972.
7. Knight, G. "Personal respirable dust samplers: Test on MSA prototype 1972"; Internal Report 73-22; February 1973.
8. Knight, G. "Respirable dust samplers: Tentative specifications and test methods"; Internal Report 73-23; February 1973.
9. Knight, G., and Schrag, K.R. "Personal respirable dust samplers: Calibration of Alberta Dept. of Health and Social Development dust samplers"; Internal Report 73-42; February 1973.
10. Knight, G., Kowalchuk, R., and Yourt, R. "Development of a dust sampling system for hardrock mines based on gravimetric and quartz (by X-ray diffraction) assessment"; Internal Report 73-52; July 1973.
11. Knight, G. "The mining personal dust sampler (MPDS) draft users manual"; Internal Report 73/54; April 1973.
12. Tchir, W.J. "Respirable dust sampling: Tests and modifications to Casella Type 113A"; Internal Report 73-65; April 1973.

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14. Knight, G. "Respirable dust samplers discussion on 'Tentative Specifications and Test Methods' "; Internal Report 73/116; June 1973.

15. Knight, G., and Cochrane, T.S. "Gravimetric dust sampling with quartz analysis and its use in metal and mineral mines"; Divisional Report 74-131; November 1974.

16. Knight, G. "The CAMPEDS Mark II Dust Sampler Manual"; Divisional Report 75/31; March 1975.

17. Stewart, B. "Collection characteristics of the two-stage respirable size selector (CAMPEDS Mark 2)"; MRP/MRL 75-48(TR); April 1975.

18. Kirk, B. "Error analysis of gravimetric and X-ray diffraction assessment of respirable dust"; MRP/MRL 75-78(TR); August 1975.

19. Knight, G. "Calibration of respirable fraction sampling equipment and quartz analysis of airborne dust samples"; MRP/MRL 76-95(OP); June 1976.

20. Knight, G., Washington, R.A.; and Gray, W.M. "A combined personal sampler for dust and radon-daughter exposure in mines"; MRP/MRL 76-122(OP); September 1976.

21. Knight, G., and Kowalchuk, R. "A comparison of gravimetric dust samplers underground"; MRP/MRL 77-40(TR); March 1977.

22. Knight, G. "Guide to gravimetric sampling with quartz analysis in mines"; MRP/MRL 77-56(TR) (Revision of 74-96); March 1977.

23. Knight, G., Thompson, E, and Treaftis, H.N. "Collection characteristics of the respirable dust size selectors used at Elliot Lake"; MRP/MRL 77-72(TR); June 1977.

24. Knight, G. "The CAMPEDS Mark II dust sampler manual"; MRP/MRL 78-88(TR) Revision of 75/31; October 1978.

25. Knight, G. "Comparisons between respirable dust samplers and testing procedures for calibration of size selection"; MRP/MRL 78-93(TR)"; December 1978.

26. Rowlandson, M. "Mass collection efficiency tests on cyclones"; MRP/MRL 79-26(TR); March 1979.

27. Knight, G. "Elliot Lake laboratory procedure for analysis of free silica using X-ray diffraction"; MRP/MRL 81-4(TR); December 1980.

28. Knight, G. "CAMPEDS mine dust sampler: Laboratory and field tests"; MRL/MRL 81-5(J); October 1980.

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10. Knight, G. "Proposed dust sampling system for miners based on a portable X-ray diffractometer - A discussion paper"; MRP/MRL 83-54(TR); June 1983.
11. Bardswich, W., Campbell, W.J., Knight, G. and Moore, E. "Workplace respirable dust monitoring - Current and proposed Canadian practice"; MRP/MRL 84-39(OP,J); August 1983.
12. Knight, G. "Proposal for particle size fraction definitions for health related sampling"; MRP/MRL 84-67(J); March 1984.
13. Knight, G. "Rationale for interpretation of airborne dust measurements at Copper Cliff sinter plant 1948-1963"; MRP/MRL 84-109(TR); October 1984.
14. Knight, G. "The use of rapid reading airborne dust instruments in mines and mills"; MRP/MRL 85-21(TR); February 1985.
15. Knight, G. "A rationale for size selective dust sampling definitions and design"; MRP/MRL

85-49(OP,J); October 1984.

16. Knight, G. "A reference size selective sampler for respirable dust"; M& ET/MRL 87-17(J); August 1986.

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General

1. Knight, G. and Cochrane, T.S. "Mines branch dust laboratory"; Divisional Report FMP 67/44-MRL; March 1967.
2. Morgan, G. "Operation and error detection using IBM Call/360 shared time computer"; Internal Report 73/130; August 1973.
3. Morgan, G. "Revision to operation and error detection using IBM Call/360 shared time computer"; Divisional Report 74/75; May 1974.
4. Knight, G. "Notes for uranium mines inspectors course first presented May, 1976"; MRP/MRL 76-86(TR); May 1976.
5. Knight, G. "Program for dust in coal mines"; MRP/MRL 80-1(TR); January 1980.
6. Knight, G. "Proposal for an extension to health and safety research by CANMET"; MRP/MRL 81-2(TR); December 1980.
7. Grenier, M.G. and Bigu, J. "Past present and future of dust research at the Elliot Lake laboratory"; M& ET/MRL 86-2(TR) 1986.

APPENDIX B

Diesel emission control studies

This appendix, the listing of reports on diesel emission control, is taken from

Heavy-Duty Diesel Emission Control: A Review of Technology. Editor E.W. Mitchell and published by The Canadian Institute of Mining and Metallurgy as CIM Special Volume 36 (1986).

APPENDIX C

Contract Research Undertaken for CANMET

This section lists some of the contractors reports on dust-related studies carried out on behalf of CANMET.

1. Gibbs G.W. and Y. Doganoglu " A study on the effect of a number of variables on three types of dust samplers" McGill University Unsolicited proposal UP-Mc-19 CANMET contract Rep. no. 6-9001 (1977)
2. Conspec Ltd. "Report on the development of instruments for the continuous measurement of radon daughters and dust" CANMET Contract Rep. No. 6-9033 (1977)
3. Conspec Ltd. "Report on the operation and performance of the underground mine environment monitoring system" CANMET Contract No. 0SQ76-00085: Contract Rep. No. 6-9034 (1977)
4. James F. MacClaren Ltd. "Industrial hygiene survey of the uranium mining and milling industry." CANMET ref. no. 6-9043 (1977)
5. Ian W. French and Associates Ltd. "Health implications of exposure to diesel exhaust emissions" CANMET Contract Rep. No. 6-9095 (1978)
6. Metrex Instruments Ltd. "Design and Development of a prototype asbestos fibre monitoring system–phase 1" CANMET Contract No. 0SQ82-0001 Contract Rep. No. 8-9139 (1980)
7. Metrex Instruments Ltd. "Development of a Microprocessor-based dust and asbestos fibre monitoring system–phase 2" CANMET Rep. No. 0-9163 (1981)
8. Brown W.D. and R.B. Bruce "Survey of Canadian laboratory practice for counting asbestos fibre levels in workplace environments" Ontario Research Foundation Report No. NMG.80-1 (1980)
9. Brown W.D. and R.B. Bruce "Survey of Canadian research and development into asbestos fibre measurement, monitoring methods and instrumentation" Ontario Research Foundation Report No. 80-2 (1980)
10. Terry A.J. and R.B. Bruce "Asbestos: Definitions, monitoring and measurement in the workplace" Ontario Research Foundation Report No. QS 310-81-1 CANMET Contract No. 0SQ80-00192 (1981)
11. Brian Mountford and Associates Ltd. "A review of underground coal mine dust control in the United Kingdom,West Germany, France,The United States and Canada" CANMET Contract No. 0SQ80-00090 Rep. No. 9-9132 (1981)
12. Memorial University: R. Parson "Review of fibrous dust problems and research requirements

in mining" CANMET Contract No. 0SU81-00143 Rep. No. 1-9007 (1982)

13. Metrex Instruments Ltd. "Development of a Microprocessor-based dust and asbestos fibre monitoring system–phase 2" CANMET Rep. No. 2-9012 (1983)
14. Metrex Instruments Ltd. "Development of sensors for separate assessments diesel exhaust particulates and respirable mineral dust in mine atmospheres" CANMET Contract No. 9SQ83-00131 Rep. No. 3-9091 (1984)
15. Laurentian University: I.A. Baldisera and K.C. Westaway "An assessment of the sulfuric acid aerosols, hydrocarbons and respirable combustible dust in the underground mine environment. CANMET Contract No. 0SU82-00179 (1984)
16. Metrex Instruments Ltd. "Field calibrations of three new asbestos fibre measuring techniques, with the existing methods in Quebec asbestos mines and mills" CANMET Contract No. 0SQ84-00299 Rep. No. 4-9152(1984)
17. McMaster University Medical Centre "Examination of the impact of polynuclear aromatic hydrocarbon exposure in underground mines" CANMET Rep. No. 4-9142 (1985)
18. J.H. Johnson and D.H. Carlson "A study to assess the effects of diesel emissions on air quality in the PCS mining Lanigan division underground potash mine" CANMET Contract No. 0SQ84-00228 Rep. No. 4-9128 (1985)
19. Mono Research Laboratories Ltd. "Production of a portable micro-processor controlled, multi size range aerosol system for use in underground mine environments" CANMET Rep. No. 4-9148 (1986)
20. the Cambrian Engineering Group Ltd.: A.S. Middleton "Investigate dust measuring techniques and identify dust levels and effects on safety, operator efficiency and cutting machine performance in potash mines" CANMET Contract No. 0SQ83-00170 Rep. No. 3-9154 (1987)